Development of a local benchmarking strategy to identify inefficient compressed air usage in deep-level mines

DL du Plooy

iD orcid.org/0000-0001-6618-7419

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

Supervisor: Dr JH Marais

Abstract

Title: Development of a local benchmarking strategy to identify inefficient compressed air usage in deep-level mines

Author: DL du Plooy

Study leader: Dr Johan Marais

Keywords: Benchmarking, Compressed air usage, Data procurement, Intra plant.

South African mines can be up to four kilometres deep, and they are continually extending to keep up with production targets as mining resources get depleted. High electricity costs and additional resources required to mine at greater depths are influencing the profitability of deep-level mines. Furthermore, as deep-level mines mature, the efficiency of compressed air networks deteriorate at a significant pace. The compressed air required to produce one tonne of ore has more than doubled in the past decade. Additionally, neglected compressed air networks result in pressure drops of up to 30%, which adversely effects production.

Comprehensive manual audits are usually conducted to identify causes of compressed air inefficiency. However, these audits are not practical in an extensive underground network. This study suggests a novel localised benchmarking methodology to locate and manage factors that contribute to the deterioration of the compressed air network efficiency.

The developed methodology was implemented on South African deep-level mines for validation purposes. The proposed methodology was able to identify underground sections with sizeable compressed air inefficiencies. The results were compared with those of conventional audit methods. It was found that the newly developed methodology was able to identify 80% of the operational improvement opportunities identified by auditing the entire underground network. The value of the newly developed methodology is evident when one considers that inefficiencies were located in less than 20% of the time it takes to conduct comprehensive audits.

Systematically implementing the methodology on a case study resulted in highlighted electricity cost savings of R7.4 million per annum while a 19% increase in production was observed. The newly developed methodology can have a significant effect on the way underground compressed air networks are maintained.

The methodology developed in this study was successfully published as a research article in the journal Sustainable Production and Consumption. The addition to the knowledge base greatly reduced audit times which will serve as a motivation for mine managers to audit underground sections more frequently. Frequent audits will result in improved service delivery and electricity cost savings of the compressed air system.

Acknowledgement

Thank you to the following whose contributions were critical to the accomplishment of this study.

- God for providing me with the knowledge and means to have completed this dissertation.
- TEMM International (Pty) Ltd, Enermanage (Pty) Ltd and ETA Operations (Pty) Ltd for funding and supplying the data.
- Dr Johan Marais, Dr Marc Mathews and Dr Philip Maré for their guidance in completing this thesis.
- Johan Jacobs and William Shaw for their assistance and knowledge shared during the implementation of this study.
- All my friends and colleagues, thank you for the support during the completion of this dissertation.
- Finally, I would like to thank my mother, whose excellence sparked the motivation in me never to fail again.

Contents

List of Figures

List of Tables

List of Equations

List of Abbreviations

CNC   Computer Numerical Control

HDD   Hopper Data Device

KPI   Key Performance Indicator

R^2 Coefficient of Determination

RFID   Radio Frequency Identification

Nomenclature

Symbol	Unit	Description
°C	Celsius	Temperature
K	Kelvin	Temperature
kg/m^3	Kilogram per cubic metre	Density per volume unit
kg/s	Kilogram per second	Mass flow rate
kJ/kg	Kilojoule per kilogram	Energy per mass unit
kJ/kg·K	Kilojoule per kilogram kelvin	Gas constant
km	Kilometre	Length
kPa	Kilopascal	Pressure
kW	Kilowatt	Power
kWh	Kilowatt-hour	Energy
kWh/t	Kilowatt-hour per tonne	Energy per mass unit
ℓ/s	Litre per second	Flow rate
m	Metre	Length
m^3	Cubic metre	Volume
m^3/h	Cubic metre per hour	Volume flow rate
m^3/s	Cubic metre per second	Volume flow rate
m^3/t	Cubic metre per tonne	Volume per mass unit
mm	Millimetre	Length
MW	Megawatt	Power
MWh	Megawatt-hour	Energy
MWh/m	Megawatt-hour per metre	Energy per length unit
Pa	Pascal	Pressure
t/d	Tonnes per day	Daily production

Chapter 1: Introduction

1.1 Background on South African deep-level mining

South Africa's economic strength is primarily due to mineral wealth of which gold and platinum group elements are the main contributors [1]. It is estimated that the mining industry made up 6.8% of South Africa's gross domestic product in 2017 [2].

Gold and platinum mines in South Africa are often deep-level mines. Platinum mines can extend to depths of 1000 m while gold mines can reach depths of more than 4000 m [3]. The profitability of mines is directly correlated to the amount of energy required for production [4]. Ore has become less feasible to access due to the greater depths at which extraction takes place [5]. Mining at greater depths increases the cost due to mining requirements and dilution due to waste rock. The effects are most evident in the South African gold mining industry: there has been a rapid decline in gold production after South Africa was the leading global producer for more than a century. South Africa's contribution to global gold production has declined from 68% to 6% in the last century [1].

South African deep-level mines are under significant stress because of increasing operational costs and low commodity prices [6]–[15]. Electricity costs in South Africa are rapidly increasing each year [4], [10], [12], [13]. The cost of electricity in the South African mining sector has increased by 238% from 18c/kWh in 2007 to 61c/kWh in 2012 [16].

The increased cost of electricity is a significant concern for the profitability of the South African mining industry, with compressed air consuming up to 21% of the electricity demand of a typical mine [4]. Underground mining mostly relies on compressed air for production even though compressed air is notorious for high generation costs [4], [9], [12], [14]. Mines still use compressed air because of infrastructure installed when electricity costs were much cheaper [9]. Additionally, compressed air systems are still used in mines because of their alterability, scalability, consistency and ease of use [17].

In addition to the increased electricity costs, the amount of compressed air required to produce one tonne of ore has drastically increased in the past decade [6]. A study of historical data illustrates that the compressed air consumption required to produce one tonne of ore in South African deep-level mines has more than doubled from 2002 to 2013 [6]. Figure 1 illustrates the compressed air volume and energy required by the compressors to produce one tonne of ore from 2002 to 2013.
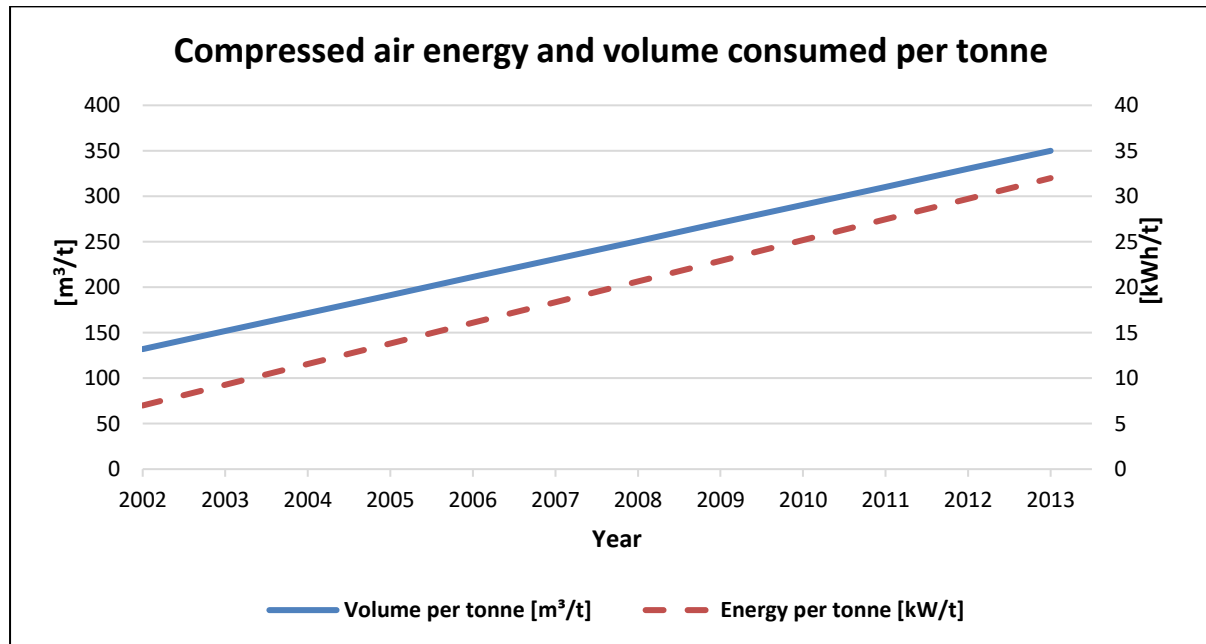
Figure 1: Compressed air energy and volume consumed per tonne of ore mined (adapted from [6]**)**

Figure 1 illustrates that the compressed air consumption to produce one tonne of ore increased from 132 m^3/t in 2002 to 350 m^3/t in 2013, and the corresponding compressor energy consumption increased from 7 kWh/t to 32 kWh/t over the same period. The strain on the profitability of mines because of high electricity costs provides motivation to focus on the operational efficiency of compressed air in deep-level mines. Although the study only includes data up to 2013, it is known that the electricity demand of compressed air systems is presently one of the leading expenditures threatening the production cost of energy-intensive mines [18]. It is therefore assumed that the efficiency of compressed air systems has worsened or at best remained the same in the five years since 2013.

As mining activity progresses and ore is extracted from greater depths, the compressed air network expands to supply energy to newly developed areas.

Expanded networks are more inefficient due to more leaks, losses and wastage present in the more extensive networks. Compressed air networks also decay over time if they are not maintained regularly. Studies found that compressed air networks are often maintained poorly [10]–[12]. Inefficiencies in the compressed air network can comprise up to 70% of the total compressed air demand [6], [8], [19].

Decaying network efficiency is, therefore, the leading cause of the increased compressed air consumption to such an extent that leaks, wastages and losses make up most of the underground compressed air demand [6], [8], [9], [19]. Network inefficiencies also cause a significant amount of pressure drop in pipe sections, which can adversely affect production [20], [21]. Compressed air network inefficiency, therefore, increases generation costs because of increased consumption and it furthermore lowers production rates because of reduced service delivery.

Because of decaying network efficiency, energy management is becoming vital for sustaining productivity in deep-level mines. However, mine operators are under tremendous pressure to meet production targets and therefore have little interest in energy management [8]. Compressed air networks can be more than 40 km long on the surface [13] and extend even further underground. Therefore, it is challenging for mine operators to locate and manage causes of operational inefficiency in underground compressed air networks [22].

1.2 Mine compressed air systems

1.2.1 Preamble

A typical deep-level mine compressed air network comprises industrial centrifugal compressors that are situated in compressor houses on the surface [7]. Compressors supply surface and underground consumers with compressed air through an intricate pipe network [10], [13]. The pipe network comprises steel pipes ranging from 150 mm to 700 mm in diameter [13].

The compressed air is supplied to various shafts and is distributed among different levels underground to the various working areas. In the working areas, the compressed air is used for various applications including pneumatic drilling, loaders

and ventilation of raise headings [14]. A typical deep-level mine compressed air layout is illustrated in Figure 2.
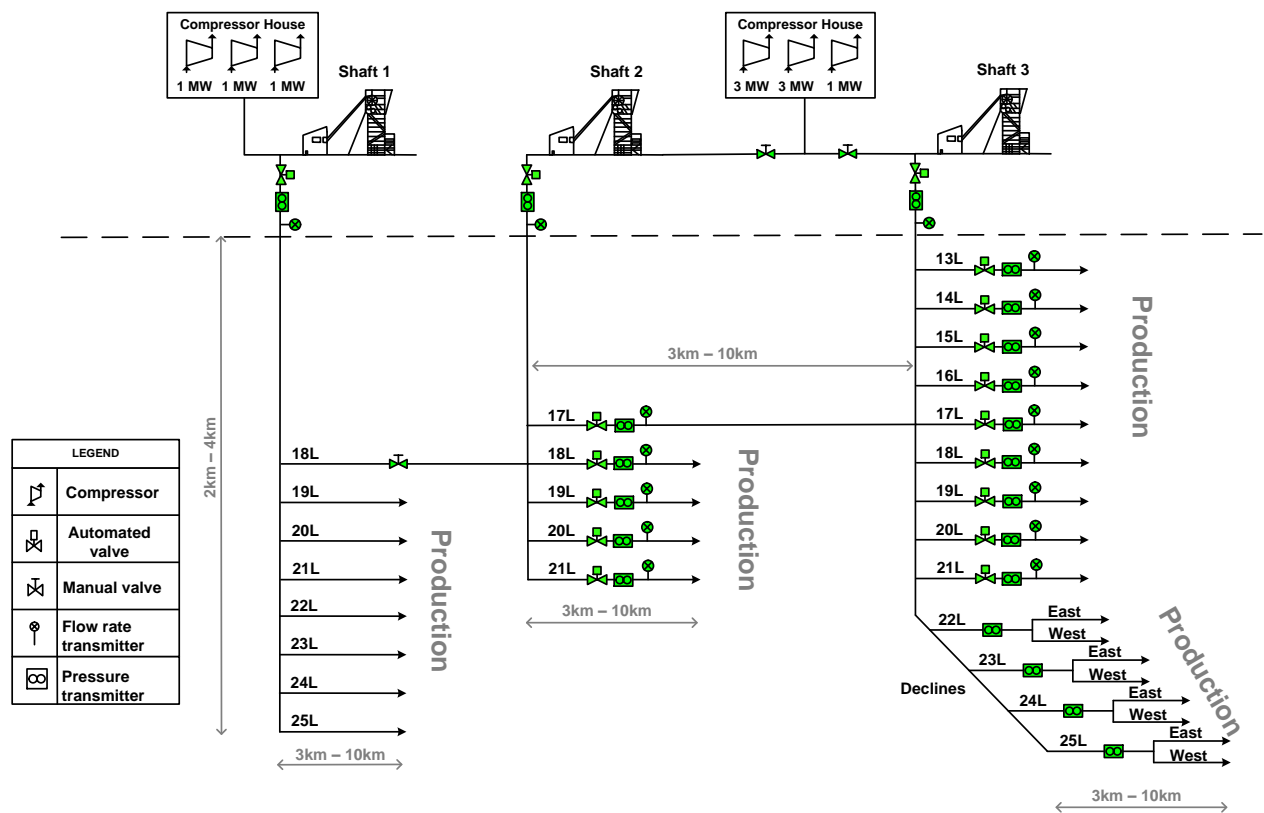
Figure 2: Typical underground compressed air network of deep-level mines

As illustrated in Figure 2, the compressed air network can extend from 2 km to 4 km below every shaft. Multiple levels are usually present below each mineshaft. The presented layout is simplified and does not contain the details of the pipe network on each level. Each level has a unique layout that is tailored to the ore reef. This is done to extract the maximum amount of ore.

The top view of a typical underground layout is illustrated in Figure 3.[1] Figure 3 presents the walkways of an individual level underground. Compressed air networks usually extend along the underground walkways. These networks can extend up to 10 km in every direction from the shaft. The walkways can contain multiple bends and

---

[1] Some of the drawings and photos do not contribute academically to this study. The references of these drawings or photos will be added as footnotes and not to the bibliography.

pathways that make each level unique. The underground compressed air network is, therefore, considered to be vast and intricate.

Figure 3: Detailed top view of a single underground level[2]

All underground and surface compressed air applications use the compressed air network as an energy carrier. The whole network must, therefore, be pressurised to supply sufficient pressure or flow, depending on the demand requirements [4]. The compressed air network can be separated into a supply and demand side. The supply side includes the compressors and pipe network that distribute compressed air to

---

[2] Layout obtained from South African mine. More details (i.e. mine name, location, etc.) may not be provided due to confidentiality agreements.

various end users. The demand side includes end users that convert pressure into mechanical energy.

1.2.2 Supply side

Multi-stage centrifugal compressors with installed capacities ranging from 1 MW to 15 MW supply the network with compressed air [10]. Two different types of surface configuration are possible [8]. The first is a dedicated supply from compressors to an individual shaft. The compressor house may contain one or more compressors with varying installed capacities. The supply capacity and the number of compressors depend on the forecasted demand of the shaft [8].

The second configuration is a mutual compressed air network among different shafts situated relatively close to each other. Compressor houses containing one or more compressor is scattered along the surface compressed air network. This type of configuration is more commonly known as a compressed air ring or ring feed configuration [10]. The compressed air network extends underground from every mineshaft to distribute air among the different mining levels.

Mineshafts of deep-level mines can extend up to 4 km deep [3], and every mining level can extend more than 10 km long [12]. The network extends to the working places of every level to supply compressed air to pneumatic drills, which are regarded as the primary consumers of compressed air in mines [11].

1.2.3 Demand side

There are different mining activities on a mineshaft during the day. Every activity has different compressed air requirements; therefore, the compressed air demand of a mineshaft varies throughout the day [8], [12]. Figure 4 illustrates the different activities during the regular operating schedule of a deep-level mine.

At approximately 04:00, workers start travelling from the surface to their various working places. The size of the cages that transport workers underground is limited, and the working places are customarily located anything from 1 km to 10 km from the shaft [12]. Therefore, it can take some workers up to two hours to reach their working places from the surface.

By 07:00, most workers have reached their working places and have started drilling. By this time, the pressure and consumption demand is at its highest to supply the pneumatic rock drills with adequate compressed air. These drills are used to drill 1.8 m deep holes into the rockface.

By 14:00, most workers have stopped drilling, which reduces the compressed air demand. Workers are now implanting explosive charges into the drilled holes during what is known as the explosive charge-up period. The explosives are detonated remotely from the surface to ensure safe operation. During the blasting shift, no mining activities are allowed, and personnel are not allowed near the working areas due to the dangerous nature of the explosive charges underground. The blasting shift is also the period with the lowest compressed air demand.

After the blasting shift, the ore is collected with winches in what is known as the sweeping and cleaning shift. The process is repeated daily.
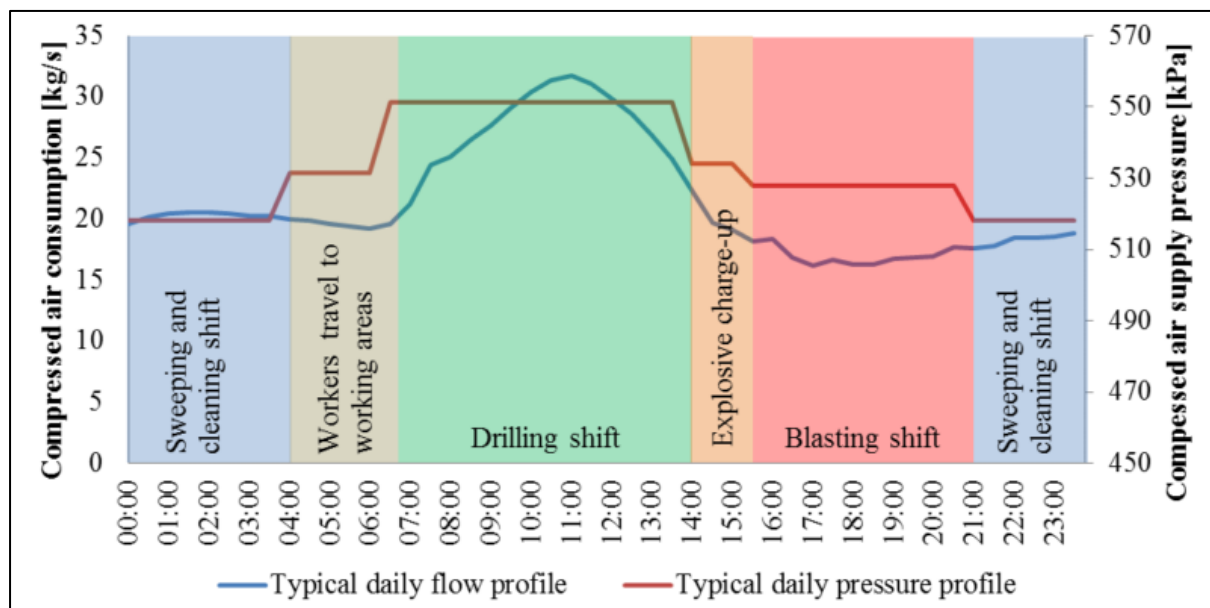
Figure 4: Operating schedule of a typical deep-level mine [12]

Compressed air is used by various underground end users that operate at different times of the day. All underground consumers are supplied from the compressed air network, which means that the user with the highest operating pressure will determine the minimum pressure requirements of the network [11]. Wastage due to oversupply

can be determined by investigating different end user operating requirements and their time of use (as illustrated in Table 1).

Table 1: Typical underground end users [7], [10]–[14]

Compressed air end users	Description	Requirement	Mining shift	Operating hours
Pneumatic rock drills	Rock drills are used to drill 1.8 m deep holes in the rockface to place explosive charges	0.08–0.7 m^3/s 400–600 kPa	Drilling	06:45–14:00
Pneumatic loaders	Loaders are used to load mined ore into loading boxes or conveyors	0.12–0.28 m^3/h 400–550 kPa	Drilling, sweeping and cleaning	21:00–14:00
Underground workshops	Compressed air is used to operate grinders, saws and drills that maintain mining equipment	0.028 m^3/h 200–250 kPa	Drilling	06:45–14:00
Pneumatic loading boxes	Loading boxes are used to load ore into skips for extraction via the shaft	0.006–0.14 m^3/h 350–600 kPa	Drilling, sweeping and cleaning	21:00–14:00
Diamond drills	Diamond drills are drills used for development, which can take place any time of the day except during the blasting shift	0.14 m^3/h 500 kPa	Varies	Varies
Refuge bays	Secure underground chambers that keep out toxic gases by maintaining a positive pressure relative to the atmosphere	0.0014 m^3/h 200–300 kPa	All	Continuous
Agitation	Open ends are used to agitate mud in dams to assist pumping operations	0.47 m^3/h 400 kPa	All	Continuous
Raise heading ventilation	Open ends are used to ventilate raise headings and provide cooling	0.019–0.091 m^3/h 350–620 kPa	All	Continuous

The compressed air application with the most significant pressure requirement governs the demand during that period. The supply from the compressors should be set accordingly to adhere to the demand requirements of the compressed air network. However, it is found that compressors are often mismanaged, which results in an oversupply of compressed air [14], [18].

1.3 Overview of operational efficiency management strategies

Operation improvement initiatives include managing the compressed air network on both the demand and supply side to obtain cost savings or improved service delivery. In some cases, an operational efficiency improvement results in cost savings and improved service delivery. An unmaintained compressed air network typically has a 20% to 50% energy savings potential by implementing cost saving initiatives [19]. Improved service delivery is typically obtained by reducing unnecessary wastage or friction in the compressed air network.

Literature is saturated with different strategies to improve the operational efficiency of compressed air systems in the mining industry. These strategies are summarised in Table 2. For a more detailed description of the included strategies, refer to Appendix A.

Table 2: Summary of compressed air system operational improvement strategies

Strategy	Reference	Summary
Guide vane control	[8], [10], [11], [13]	The air supply of individual compressors is controlled by regulating the guide vane angles on the air intake of the compressor. Lowering the discharge airflow rate of the compressor puts less strain on the driving motor, which results in less energy generation. Shortcoming: The amount of air that can be reduced is limited by the required demand.
Load sharing	[7], [10], [11]	Different compressors vary in size and efficiency. Most compressed air networks have different types and sizes of compressor installed. Energy savings can be achieved when the most efficient compressors share the load of the compressed air demand. Shortcoming: Mines prefer to cycle the running times of compressors equally to minimise maintenance.
Compressor selection	[8], [11]–[13]	Because compressed air demand varies during the day, compressors are scheduled appropriately to avoid an oversupply of compressed air. Compressor running schedules are thus optimised to supply the required demand with the least number of compressors active. Shortcoming: Optimisation is limited by the required compressed air demand.

Strategy	Reference	Summary
Control valves	[10]–[12]	Air demand can be regulated with control valves installed on surface and underground. Valve openings are varied to regulate the amount of air that passes through the valve and so doing, controls the downstream pressure of the compressed air network. Control valves are used to prevent an oversupply of compressed air and to minimise wastage through leaks when the compressed air demand is low. Shortcoming: The amount of air that can be reduced is limited by the required demand.
Reducing wastage	[9], [11], [21], [23]	Any wastage of compressed air can cause a significant increase in the compressed air demand. Compressors need to consume more energy to satisfy the increased demand, which leads to higher generation costs. Leaks are the most significant contributor to compressed air wastage in mines. In poorly maintained systems, up to 50% of the compressed air consumption can be wasted through leaks. Additionally, leaks can cause air pressure losses of up to 30% from the supply to the working areas, which adversely affect production rates. A leak in a compressed air system is defined as any opening where compressed air is released into the atmosphere without authority or unintentionally. Shortcoming: Wastage is extremely difficult to locate and manage in an extensive underground network. Currently, leaks and other losses are managed through manual inspections of the pipeline.
Reducing friction losses	[6], [7]	Pressure losses occur in pipe sections because of pipe friction; therefore, longer sections will experience more pressure losses than sorter sections. Certain factors can contribute to the friction inside a pipeline. These factors include bends, blockage, corrosion and varying diameters. Losses experienced from inefficient pipe network configurations can unfortunately only be rectified by replacing/ reconfiguring the pipe network or sections of the pipe network. Shortcoming: Currently, there is no way to locate and quantify causes of friction losses in the mining industry.

To implement the strategies in Table 2, the potential for operational improvement must first be identified. Literature is saturated with methods on how to locate and quantify the potential improvement for some of the mentioned strategies, namely, guide vane control, load sharing, compressor selection, and control valves [7], [8], [10]–[13]. However, little research has been done in the mining industry on how to identify the potential for improving compressed air inefficiencies due to wastage and losses.

Some of the most effective operational improvement methods discussed in Table 2 are limited to the required compressed air demand. Therefore, the demand side must be optimised to get a significant improvement at the supply side. However, identifying some of the demand-side initiatives is a challenging task.

Currently, no method exists to locate and manage the wastage and losses of an underground compressed air network other than doing regular manual audits of the entire network [24], [25]. Other techniques that are available to identify system inefficiencies are discussed in the next section.

1.4 Techniques to identify system inefficiencies

1.4.1 Preamble

The previously mentioned operational improvement initiatives can contribute substantially to electrical energy savings and improved service delivery. However, before improvement initiatives can be implemented, areas where optimisation can be achieved must first be identified [12], [15].

Literature covers many compressed air energy management techniques that can be used to identify inefficiencies. Different techniques can identify compressed air inefficiencies on different levels ranging from pipe sections to entire plants. The relevant techniques and their applicability to an underground mine network are discussed in the sub-sections that follow.

1.4.2 Leak detection methods

Leaks in compressed air systems can contribute up to 50% of the wastage [21] and can cause pressure drops of up to 30% in pipelines supplying workplaces [23]. Rectifying leaks is considered to be the most effective method of improving a compressed air system [24], [25].

A study was done by Murvay and Silea to identify the state-of-the-art leak detection methods [26]. Murvay and Silea classified leak detection methods based on their technical nature. Two main categories were distinguished, namely, hardware and software-based methods.

Hardware-based methods use specialised equipment to detect gas leaks. Different hardware techniques exist that are based on the type of equipment used. These techniques include monitoring soils, sampling vapours, using cable sensors, and doing acoustic and optical measurements. Each of these methods is briefly described in Table 3.

The equipment used for hardware detection methods is either handheld or permanently installed equipment. For handheld equipment, personnel are required to patrol the pipeline to detect leaks. Patrolling an extensive underground pipeline on a continual basis is resource and time intensive; therefore, methods that require handheld devices are not considered practical to use in underground deep-level mines. Other shortcomings are also briefly explained in Table 3.

Table 3: Summary of hardware leak detection methods [20]–[22], [24], [26]–[31]

Method	Description	Shortcoming
Acoustic sensors	Acoustic sensors are used to detect noise emanating from gas leaks.	Handheld devices require personnel to patrol the entire pipeline.
Optical sensors	Emitted radiation caused by gas molecules is monitored to determine leaks. Permanently installed or handheld devices are used.	Handheld devices require personnel to patrol the entire pipeline.
		Devices required for optical leak detection are costly.
Cable sensor	Optical fibre cables are installed in proximity of the pipeline to monitor a series of physical and chemical properties that can signal a leak.	High implementation costs.
		Challenging to retrofit to existing pipelines.
Soil monitoring	Tracer compound is injected into the pipeline and instrumentation is used to monitor soil for the traces of the compound to indicate leaks.	Not applicable to exposed pipelines.
Vapour sampling	A vapour sampling test tube is buried along the pipeline, and portable detectors are used to investigate test tube samples to determine leaks.	Frequent patrols of the pipeline are required to investigate sampling.
		Not applicable to high depth or above ground pipelines.

Software-based methods implement algorithms that continually monitor the state of the compressed air system on various locations to determine if leaks are present.

There are different software methods based on the different approaches that these methods use to determine leaks. These methods include: mass/volume balance, real-time transient modelling, negative pressure wave, pressure point analysis, statistics and digital signal processing. Each of these methods is briefly described in Table 4.

Temperature, pressure and flow rate are the most common parameters that these methods use to determine leaks. Most of these methods require the instrumentation that monitors these parameters to be installed at regular intervals along the pipeline. Installing sufficient instrumentation for data acquisition on an entire underground network is not feasible due to extremely high costs and difficulties to retrofit existing pipelines. Other shortcomings of software-based methods are briefly discussed in Table 4.

Table 4: Summary of software leak detection methods [28], [29], [32]–[35]

Method	Description	Shortcoming
Mass/volume balance	The inflow and outflow of a pipeline are measured to determine any losses in the pipeline. This method is used to determine if a leak is present.	Cannot be used to locate a leak.
		Cannot be used in transient conditions.
Real-time transient modelling	Flow rate, pressure and temperature measurements are used in pipe flow models to determine leaks.	Extensive instrumentation is required to collect sufficient data.
		The employed models are involved, and they require a trained user.
Negative pressure wave	Pressure transducers installed at both ends of a pipeline are used to pick up negative pressure waves caused by occurring leaks.	Not practical for long-range pipelines due to the dissipation of pressure waves.
Pressure point analysis	Pressure transducers are installed at frequent intervals along the pipeline to pick up negative pressure waves caused by occurring leaks.	Extensive instrumentation is required to collect sufficient data.
		Not reliable for transient conditions.
Statistical	Statistical analysis of pressure and flow changes on multiple locations along a pipeline is used to locate leaks.	Extensive instrumentation is required to collect sufficient data.
Digital signal processing	Pressure and flow readings are used in conjunction with digital signal processing to	Difficult to implement, test and retrofit.

Method	Description	Shortcoming
	determine a change in system response. Leaks can be detected even if noisy data is present.	Extensive instrumentation is required to collect sufficient data.

The hardware- and software-based leak detection methods were explained briefly in Table 3 and Table 4. The main difference between hardware and software-based methods used to detect leaks is that hardware-based methods require some form of external hardware (usually handheld devices) whereas software-based methods use data received from permanently installed devices. Although these methods have been proven to work for specific applications, they have not been implemented in the mining industry yet. Table 3 and Table 4 indicate the shortcomings of using these methods in an underground compressed air network of a deep-level mine. The shortcomings clearly show why these methods are not used in the mining industry.

1.4.3 Pressure drop test

Pressure drop tests are done to monitor the state of a compressed air section. Manual or automatic isolating valves are closed to isolate the compressed air flowing to a pipe section. Usually, this is done on every level underground. When the airflow supply is closed off, the time it takes for the pressure to drop to atmospheric pressure (0 kPa gauge pressure) is measured for each section. The time is compared with previous tests to determine the condition of a pipe section. If the pressure has dissipated quicker than the previous pressure drop test, it is an indication that wastage due to leakage has increased for that section [12].

This result of the test is, however, not comparable when the conditions of the pipe section have changed; for example, if a section has been expanded or active working areas have moved [12]. Opportunities to conduct pressure drop tests are also limited because pipe sections must be isolated completely. Therefore, these tests are usually conducted on off-production weekends to avoid production losses [12].

The biggest problem with pressure drop tests is not the limited time to conduct tests or the ever-changing network conditions, but the mechanical problems associated with isolation valves. The seams of the valves are often damaged, which allow air to flow through when these valves are in the closed position [12]. An example of a damaged

butterfly valve is presented in Figure 5. The illustrated valve is damaged to a point where it is not capable of isolating the air. When the air cannot be isolated completely, the pressure drop test becomes incomparable.

Figure 5: Damaged butterfly valve[3]

In addition to the challenges faced with pressure drop tests, the results of a pipe section can only be compared with previous results of the same section to determine possible deterioration. Because of different operating conditions and varying pipe section distances, the results of different pipe sections cannot be compared to determine which section is the most inefficient user of compressed air.

The results of pressure drop tests are only useful for detecting deterioration because of leaks. Other sources of inefficiencies, for example, friction losses and oversupply of compressed air, cannot be detected.

1.4.4 Simulations

Mine operations are simulated with computational software to analyse the results of possible scenarios. Simulation software integrates multiple theoretical formulas to calculate the impact of changes made to a system. A simulation model is developed

---

[3] Kentintrol, "Supplied control valve", Brighouse, West Yorkshire. [Online]. Available: https://kentintrol.com/severe-service-valves/deluge-fire-system/ [30 July 2018].

to mimic mine operations as closely as possible. Some mine compressed air systems have been simulated with an average error of only 2% [14].

Simulation software has been used in the mining industry to evaluate operational improvement initiatives of the compressed air system [7], [14]. However, possible improvement opportunities must be identified first, which requires experience and knowledge of the compressed air system.

These simulations require an abundance of data at various strategic locations in the compressed air system including but not limited to pressure, temperature, power and flow rate data [36]. Obtaining the required data for an accurate simulation requires extensive time and resources [18]. Therefore, previous studies on compressed air simulations in mines were limited to surface operations [7], [14].

Although simulation procedures are powerful tools to evaluate the impact of initiatives, it should be considered that simulation software is expensive and technically challenging (requires skilled workers), and requires an abundance of data to model a system accurately [18].

1.4.5 Benchmarking

Energy benchmarking is recognised as an effective method to evaluate energy efficiency and is commonly used in the industry as an energy management technique to improve the performance of energy utilisation [37]–[45]. Benchmarking is done within the context of assessing comparative energy efficiencies and can be defined as evaluating performance compared with some reference performance [4].

Benchmarking includes developing quantifiable energy-related indicators known as key performance indicators (KPIs). KPIs of different plants or systems are compared among peers with similar operations or previous states of the same plant/system. By analysing and comparing KPIs, valuable insight can be gained into the energy and resource efficiency of different plants or systems [4], [37], [43].

Various benchmarking studies have been implemented to determine the efficiencies of different mines or mine systems. Unfortunately, it is not always feasible to make complex comparisons between different mines or systems [39]. This is due to the

limited resources, measuring equipment and time required to gain information from different mines.

A benchmarking study done in a processing plant applied a benchmarking methodology on line level to identify the energy use of each computer numerical control (CNC) machine per product produced [39]. The results of the study reflected the energy use and wastage of different CNC machines in the same plant. The performances of different CNC machines were compared to gain insight into their efficiencies.

A thorough review of literature found that no benchmarking methodologies have been implemented on line level in the mining industry. Benchmarking compressed air networks on line level could be used to determine efficiency and wastage of different mine sections if an appropriate comparison method is developed.

1.5 Problem statement and overview of the study

1.5.1 Preamble

The problems and difficulties to identify improvements on compressed air networks in deep-level mines are briefly summarised in this section to determine the objectives of this study. An overview is presented containing the content of each chapter in this document.

1.5.2 Problem statement

Compressed air systems are one of the largest electricity consumers in the mining industry. The rapid increase of electricity has led to investigations on compressed air efficiency. It was found that compressed air system efficiencies decay at an alarming rate as compressed air networks extend and decay over time.

Compressed air inefficiencies present an opportunity to reduce energy expenditure and increase service delivery with minimal investment [46]. The existing research related to operational improvements of mine compressed air systems, discussed in Chapter 1.3, proved that most studies are done in isolation. Supply-side initiatives are limited by the required demand of compressed air. Therefore, demand-side initiatives

including the rectification of wastage and losses should be implemented to maximise the effectiveness of supply-side initiatives.

Currently, locating and managing the wastage and losses of an underground compressed air network are limited to regular manual audits of the entire network [24], [25]. As underground compressed air networks become more extensive and complicated due to continued expansion and development, it becomes unpractical to do manual audits on a regular basis. Therefore, there is a need for a practical method to locate inefficient compressed air usage in an extensive underground network without any expensive instrumentation or many resources.

The literature review in Chapter 1.4 proved that existing techniques used to identify system inefficiencies are limited in the mining industry. None of the conventional leak detection methods are practical to implement in an underground mine.

Tests that are usually performed to monitor the state of the pipe network include pressure drop tests. These tests can determine if a pipe section has deteriorated, but mechanical problems and extending pipe sections influence the applicability of these tests. In addition, the infrastructure required to conduct pressure drop tests are costly to install on multiple sections underground.

Simulation software provides a powerful tool to evaluate initiatives. However, previous simulation studies of mines have been limited to surface operations because of the extensive time and resources required to simulate underground conditions.

Benchmarking is recognised as a method to evaluate system efficiency. It has been used to evaluate and compare the efficiency of different machines on line level in a process plant. Although benchmarking has been implemented in the mining industry to evaluate the performance of different mines, it has not been implemented on line level for intra mine comparisons. Benchmarking different sections of the compressed air network in a deep-level mine should provide valuable insight into the efficiency of the network on line level. By comparing the performance of different pipe sections, underground awareness can be acquired into which sections are not utilising compressed air efficiently.

1.5.3 Research objective

Locating inefficiencies in an underground network with minimal effort will serve as a valuable energy management support tool for mine managers with little interest in energy management [39].

This study aims to provide a practical method to implement local benchmarking in a deep-level mine to locate compressed air inefficiencies. Mine sections should be prioritised to guide improvement efforts of the compressed air network that will result in increased operational efficiency of the entire compressed air network.

The work presented in this study led to an article that was successfully published in an international journal (see Appendix B). The author of this dissertation is the leading author of the article.

1.5.4 Overview of the study

Chapter 1 – The introductory chapter consisted of background relevant to the study. Firstly, the electricity usage and severe increase in compressed air consumption in deep-level mines were investigated. The methods to detect local inefficiencies in an underground compressed air network were presented to form the need and objective of the study.

Chapter 2 – This chapter includes existing research relevant to the need of the study. Benchmarking and the associated difficulties of implementing benchmarking on a local level are reviewed. Previous studies, relevant to benchmarking in deep-level mines, are critically reviewed to mitigate the associative difficulties of implementing benchmarking methodologies.

Chapter 3 – A method is developed to implement benchmarking locally in deep-level mines. The developed methodology considers the associated difficulties discussed in Chapter 2. The first phase of the methodology is to develop a practical method of obtaining data at a deep-level mine with limited infrastructure.

The second phase is to develop a benchmarking methodology with the relevant obtained data. Benchmarking is done to prioritise improvement efforts to improve the

operational efficiency of the compressed air system. The last phase is developing a procedure to validate the developed methodology.

Chapter 4 – This chapter serves as validation of the developed methodology. The methodology and compressed air improvement initiatives are implemented on real case studies. The results of the improvement efforts are compared with prioritised levels obtained from the developed methodology. The improved operational efficiency is validated with a regression analysis before and after initiatives were implemented.

Chapter 5 – This chapter serves as a conclusion to the study. The study is summarised, and conclusions are made from the obtained results. The limitations of this study and recommendations for future work are also discussed in this chapter.

Chapter 2: Literature Study on Benchmarking

2.1 Preamble

The difficulties associated with implementing benchmarking studies are highlighted in this chapter. An in-depth review of the various factors that influence the practicality of existing benchmarking studies are presented. Previous benchmarking studies that apply to the mining industry are critically evaluated to determine their related difficulties and mitigation strategies.

A study done by Ke *et al.* analysed the energy benchmarking practices used in industry [42]. Process-based energy benchmarking, where energy-intensive processes are compared, was analysed in detail from the perspective of systems engineering. It was determined that a great deal of effort is required to implement energy benchmarking in real-world applications. Three areas contribute to the difficulties associated with benchmarking.

First, variable energy governing factors play a role in the accuracy of benchmarking. Mathematical transformation, grouping and reasonable assumptions are required for accurate comparisons [3], [4], [39], [42], [47], [48]. These mitigation strategies require an in-depth knowledge of compressed air systems to implement them correctly. Additionally, the accuracy of a mathematical transformation formula is highly dependent on the number of case studies available for the derivation. The same is true for grouping techniques.

Second, sub-processes in industrial production systems are often non-linear and complex. As a result, it is sometimes difficult to determine cause-and-effect relationships between energy processes and production outputs [37], [42], [43]. Benchmarking studies use KPIs to compare peers. Choosing an appropriate KPI is challenging if a cause-and-effect relationship cannot be determined within the compressed air system.

Third, some facilities lack energy measurement and management [12], [42], [49]–[52]. Obtaining suitable and accurate data for benchmarking can, therefore, be challenging. Obtaining data underground is especially challenging as deep-level mines often do not

have measuring instrumentation installed underground. However, underground compressed air data is critical if different underground sections are to be benchmarked.

To implement a practical benchmarking methodology, the three areas of difficulties associated with benchmarking should be addressed and mitigated. Previous benchmarking studies provide different methods of dealing with the associated difficulties.

2.2 Energy governing factors

Every mine is unique regarding energy governing factors such as infrastructure, depth, technology, environment and allocation of resources. These energy governing factors influence the energy usage of each mine. Multiple studies on benchmarking in mines were able to implement complex grouping and mathematical manipulation to compare different mines with relative accuracy [4], [47], [48], [53], [54].

Energy benchmarking studies of mines highlight the difference between global and local benchmarking and the difficulties faced when comparing mines with variable energy governing factors. Benchmarking the total aggregated usage to compare different plants is known as global benchmarking. Some of the relevant global benchmarking studies are discussed below.

Tshisekedi's study on energy consumption standards and cost included energy benchmarking for gold and platinum mines [54]. The total energy consumption of all systems was used to determine the energy intensity in kilowatt-hour per tonne milled. The benchmarking was used to gain insight into the total electricity consumption of different mines. However, Tshisekedi reported that the accuracy of benchmarking could be increased significantly if different systems, for example, compressed air and water reticulation systems, were benchmarked individually.

A study was done by Van der Zee that comprised benchmarking high usage systems of gold mines, which included benchmarking compressed air electricity usage based on production in kilowatt-hour per tonne [48]. By benchmarking different systems instead of the total electricity usage, a more accurate comparison could be made between the benchmarked results of different mines. Additionally, different energy

governing factors were considered including mine technology, mining depth, mine operation size and mine profitability. Grouping was done where similar mines were compared based on the different factors to provide a more accurate benchmarking for electricity usage improvements.

Cilliers benchmarked various mines based on compressed air electricity use and production [4]. Variable energy governing factors including ambient conditions and mine depth were taken into consideration by determining their effect on energy consumption with mathematical regression models. The benchmarking results were normalised based on the mathematical formulas developed from these regression models to accurately compare mines with different energy governing factors.

From the studies it was determined that variable factors such as infrastructure, depth, technology, environment and allocation of resources play a significant role in the accuracy of energy benchmarking. The previous studies evaluated the usage and production of an entire mine and then compared the findings to other mines with similar variable factors. The variable factors could be made constant if different sections of the same mine were compared, which would simplify and increase the accuracy of benchmarking.

A study done by ElMaraghy et al. on local benchmarking in the industrial sector found that it is not always feasible to obtain the required information to make complex comparisons for global benchmarking [39]. This is due to the limited resources, measuring equipment and time required to gain information from different plants. The study emphasised the need for local benchmarking to mitigate the challenges faced by comparing data from different plants.

Local benchmarking can be defined as an intra plant comparison of KPIs [39]. Performance measures are evaluated within plants to benchmark performance of different sections on the same plant. Local benchmarking can be used to locate and quantify inefficiencies on line level. A thorough review of energy benchmarking literature found no instances of local benchmarking in the mining sector. There is, therefore, a need for benchmarking on line level in the mining sector to mitigate complex grouping and mathematical manipulation techniques used in previous global benchmarking studies [4], [47], [48], [53], [54].

2.3 Evaluating suitable key performance indicators

Benchmarking studies use different KPIs to compare and evaluate the operational efficiency of different plants or systems. The typical types of indicator are specifically energy consumption and energy intensity. Specific energy consumption is defined as the ratio of energy consumption to a specific output or product. Energy intensity is defined as the ratio of energy consumption to some monetary value.

Increased operational efficiency is reflected when a decrease in specific energy consumption or energy intensity is achieved. Energy intensity indicators are useful on aggregated plant or sector level, and specific energy consumption indicators are more suitable for comparison of systems such as compressed air [37].

Bunse *et al.* did a gap analysis between industry needs and existing literature on energy efficiency [37]. The analysis found that KPIs are in abundance on aggregated plant level, but that KPIs suitable to local benchmarking are still absent. Furthermore, a study done by May *et al.* found that KPIs calculated on aggregated measures of consumption do not consider energy inefficiencies [43]. The study determined that there are insufficient guidelines available for the development of KPIs. Additionally, current KPIs lack the consideration of cause-and-effect relationships between energy-related performance and production output [43].

Previous mine benchmarking studies, which included compressed air systems, used the ratio of generated compressor energy to production output in kilowatt-hour per tonne milled as an appropriate KPI for comparison [4], [12], [48]. The same KPI is not applicable at a local level since the generated energy of compressed air cannot be allocated to different sections of the same compressed air network. Therefore, a different KPI needs to be developed for appropriate intra mine comparisons.

Previous studies indicate that KPIs should be developed on some theoretical basis that considers the relationship between the input and output of a system [41], [43]. Thus, to determine which variables are applicable to use for a KPI on a local level, mining operations applicable to different mining sections are investigated. KPIs are based on an input-to-output ratio. In the case of an underground mine compressed air system, pneumatic drills use compressed air for production. Rock drill operators have

limited time during their shifts to drill holes in the rockface. If more holes are drilled in the rockface, more explosives can be inserted to obtain more ore and increase production rates. Rock drills are maintained regularly to keep production rates optimal. Therefore, the performance and air consumption of different drills should not vary considerably. If it is assumed that the performance of drills is constant throughout the mine, then there should be a strong correlation between production and compressed air consumption.

Theoretical equations that govern compressed air energy are investigated to determine the relationship between compressed air consumption and production. The mechanical energy required per mass unit of air is expressed in Equation 1.

Equation 1: Mechanical energy required by a centrifugal compressor to compress air [7]

$$W_{comp} = \frac{nRT_{in}}{\eta_{comp}(n-1)}\left(\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right)$$

Where:

W_{comp} Mechanical energy per mass unit [J/kg]

n Polytropic constant for isentropic compression [–]

R Gas constant for air [J/kg·K]

T_{in} Compressor inlet temperature [K]

η_{comp} Compressor efficiency [–]

P_2 Compressor discharge pressure [Pa]

P_1 Compressor inlet pressure [Pa]

The power required by the compressor to produce compressed air at a specific rate is then calculated with Equation 2.

Equation 2: Compressor power [7]

$$P_{comp} = \dot{m}_{air} \times \dot{W}_{comp}$$

Where:

P_{comp} Compressor power [W]

$\dot{m}_{air}$ Mass flow rate [kg/s]

W_{comp} Mechanical energy per mass air unit [J/kg]

Equation 2 illustrates that the power required by a centrifugal compressor directly correlates to the mass flow rate that the compressor produces. Installed meters on mines usually measure compressed air as volume flow rate and not as mass flow rate. Mass flow rate can be converted to volume flow rate with Equation 3.

Equation 3: Mass flow rate conversion [55]

$$\dot{m} = Q \times \rho$$

Where:

$\dot{m}$ Mass flow rate [kg/s]

Q Volume flow rate [m³/s]

ρ Density of air [kg/m³]

The density of air is required for this conversion, which can be calculated with the ideal gas law presented in Equation 4.

Equation 4: Ideal gas law [55]

$$\rho = \frac{P_{abs}}{RT}$$

Where:

ρ	Density of air [kg/m^3]
P_{abs}	Absolute air pressure [Pa]
R	Gas constant for air [J/kg·K]
T	Air temperature [K]

It should be noted that the mass flow rate and volume flow rate of air are measures of the amount of air supplied to the network. For this study, these measures are referred to as compressed air consumption. Unfortunately, the relationship between compressed air consumption and production cannot be determined from first principles. However, the experimental results of previous studies are used to derive such a relationship. Cilliers' study included a regression analysis to determine the relationship of generated compressor energy and ore mined [3]. The regression analysis was done during summer and winter to consider the ambient conditions as an energy governing factor. The results of the study are presented in Figure 6 and Figure 7.
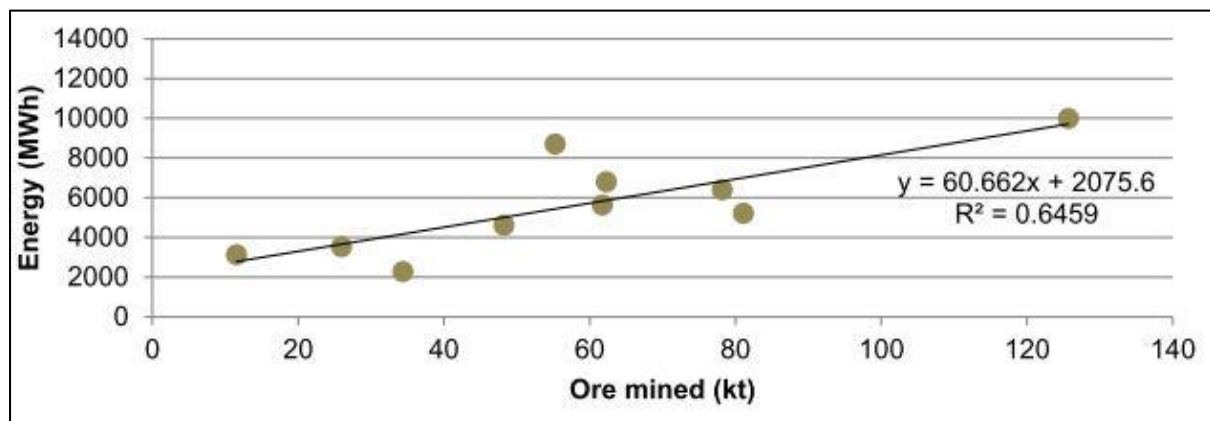
Figure 6: Generated compressor energy versus ore mined (summer) [3]
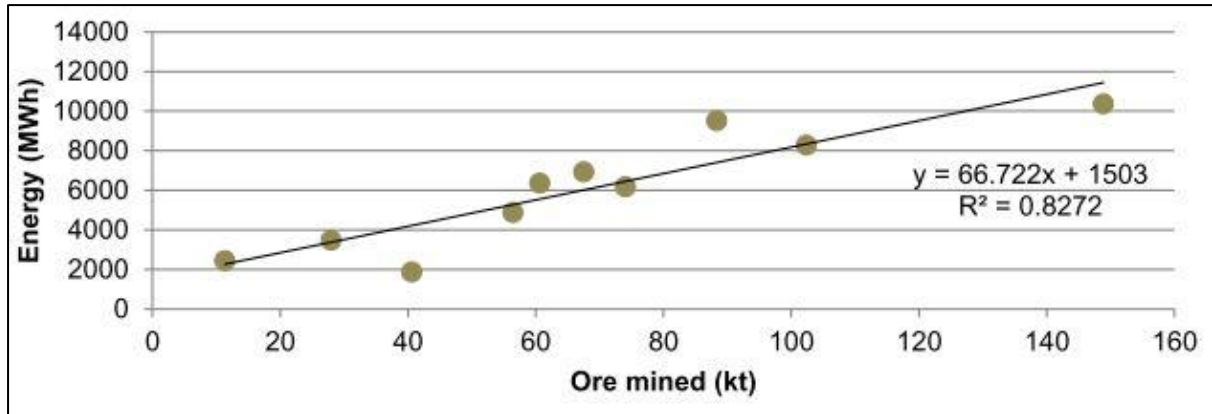
Figure 7: Generated compressor energy versus ore mined (winter) [3]

The results of the analysis suggest a strong linear correlation between generated compressor energy and ore mined. The validity of the regression analysis is supported by high coefficient of determination (R^2) values during summer and winter months. However, the amount of energy generated by a compressor cannot be allocated to different sections of a mine. The generated energy of a compressor is defined as the power output of a compressor over a specific period. Therefore, the generated energy can be converted to compressor power, which is described by the compressor power equation (Equation 2).

By combining the experimental results found in Cilliers study [3] between compressor energy versus ore mined and the theoretical relationship of compressed air consumption versus compressor energy, there should be a strong correlation between air consumption and production.

By measuring the compressed air consumption per section at some determined point upstream of the drills, any wastage or losses present from the measuring point to the drills will increase the compressed air consumption of that section. From the determined relationship between consumption and production, it is evident that any inefficient usage of compressed air should be detectable from sections with a reduced ratio of compressed air consumption to ore produced (input to output).

2.4 Existing underground infrastructure and measuring techniques

2.4.1 Review of existing mining infrastructure

Sufficient data, such as pressure and power, and information, such as layouts and number of working areas, are critical to characterise the current system accurately and to identify areas for improvement [12], [18]. Energy management techniques rely on accurate data to identify improvement initiatives and to monitor the impact of the improvements.

Ital and Lu conducted a study on plant obsolescence and found that it is becoming increasingly difficult to maintain information and control systems. Additionally, some original equipment manufacturers are going out of business and discontinuing support [49].

Lakshminarayan, Harp and Samad used case studies to illustrate that actual data in industrial databases is unavoidably incomplete [50]. The problem of obtaining sufficient data is, therefore, a global problem that is present in all industries. The problem is also applicable to mining industries since mining managers are under tremendous pressure to meet production targets and therefore neglect development and maintenance of control systems [8].

The compressed air network of a mine that is well instrumented should have a control valve, a programmable logic controller, and a pressure- and flow transmitter installed. Installation is done at strategic locations to control the compressed air demand and to monitor the state of the underground compressed air system [12]. It is found that mines often have instrumentation installed on the supply side to ensure that the compressors are functioning correctly and supplying a sufficient amount of compressed air. However, many mines do not have sufficient compressed air monitoring instrumentation installed underground [12], [18].

Monitoring instrumentation and control systems in the mining sector are decades behind more progressive sectors, which negatively affects the productivity and performance of mining projects [51], [56]. Tremendous financial pressure and progressively limited access to capital in the mining industry [51] have resulted in a reluctance to spend capital on expensive instrumentation. Installing compressed air

monitoring and control instrumentation on every underground section requires great capital expenditure [10]–[12]. Therefore, mines often opt to install instrumentation at the supply side on the surface only.

Limited measuring instrumentation underground presents a problem for compressed air benchmarking studies on a local level. Local benchmarking requires comparisons to be made between the performance of different sections on the same mine. To evaluate the performance of a section, the consumption and production of that section should be quantified.

Obtaining production data should not be a problem as mines are adamant about the amount of ore they produce [8]. Scales are typically installed underground on every level to measure the ore produced from different sections. In smaller shafts, only the total amount of ore produced is measured on the surface. However, for this study, small shafts are not applicable as they do not have an extensive compressed air network. As a result, energy management of the compressed air should not be a problem.

Unfortunately, the compressed air consumption data for different sections underground is not as readily available as the production data. With limited infrastructure available, manual measurements have to be conducted to obtain data [12].

2.4.2 Shortcomings of existing measuring techniques

Without sufficient instrumentation installed to characterise the underground compressed air demand, data has to be procured manually with portable instrumentation [12]. The only way to accurately characterise a compressed air network demand is to measure the compressed air flow to relevant sections [12], [46]. Portable instrumentation is used to obtain data at strategic locations. However, the flowmeters used to obtain data can be very expensive, technically challenging to set up and, in some cases, challenging to install [46].

Various types of flowmeters are available. Almost all flowmeters are technically challenging because of the need to compensate for varying conditions such as pipe diameter, atmospheric pressure and atmospheric temperature. Orifice plate

flowmeters are not as expensive as other flowmeters, but they are difficult to install. Installing orifice flowmeters requires the pipe section to be isolated and depressurised. The depressurised pipeline must be cut to install the flowmeter spool in-line of the compressed air pipe section to collect data. After the study, the entire process must be reversed to remove the flowmeter. Because of the continuous nature of a mine's compressed air demand, mines cannot afford to isolate entire sections of the compressed air network. The cost associated with the installation is another reason why this method is not practical in mines that are under financial pressure.

In-line, venturi differential flow, rotary and pulse count meters are other more expensive flowmeters. These flowmeters have the same impractical installation requirements as the orifice plate flowmeter. Another drawback is that when these meters are installed, they can cause pressure drops as well as blockages due to contaminants.

Insertion-type flowmeters are portable flowmeters that can be inserted into the pipeline via a valve opening. A probe attached to a rod is used to protrude the pipeline and obtain measurements. Insertion flowmeters can be installed while the pipeline is pressurised; there is no need to isolate pipe sections. Among the various types of flowmeter available, insertion-type flowmeters offer the most practical way to obtain data in an underground mine. Unfortunately, this type of flowmeter is also the most expensive [46].

Because flowmeters are so expensive and unpractical in underground mines, auditees typically calculate the compressed air demand from various pressure meter and ampere meter measurements from the compressors [46]. The manufacturer's stated capacity is used to determine the discharge flow of compressors at an ampere reading and pressure output. Calculating the flow using this method is often inaccurate and gives no insight into underground demands.

Auditees use pressure loggers to obtain pressure data because of their low cost compared with flowmeters as well as their simplicity. Pressure loggers can be installed without difficulty at any valve opening without having to compensate for any varying conditions.

For this study, the limited infrastructure available should be considered. An alternative method should be investigated to obtain data underground that does not involve costly flowmeters.

2.5 Summary

The different areas that contribute to the difficulties associated with benchmarking were discussed throughout this chapter. The first area, namely, the varying energy governing factors that influence benchmarking results, was mitigated in previous studies through mathematical manipulation, grouping or reasonable assumptions. It was found that by implementing local benchmarking, the energy governing factors should not vary significantly for different mining sections. Therefore, these factors should not influence the benchmarking results in this study.

The second associated area of difficulty was determining cause-and-effect relationships to select an appropriate KPI for benchmarking. The practices of evaluating KPIs and previous KPIs pertaining to compressed air systems were investigated. The relationship of compressed air consumption and production in a mine was evaluated with a combination of theoretical equations and experimental results. It was determined that compressed air consumption and the amount of ore produced would serve as appropriate variables for a KPI.

The third associated area of difficulty was the measuring instrumentation required to obtain sufficient data for benchmarking. A review of existing infrastructure in mines found that the underground compressed air instrumentation required for local benchmarking is in most cases not sufficient. Manual measurements are therefore required with portable instrumentation to obtain adequate data. Unfortunately, the conventional equipment used for data procurement is not practical for underground use. Another means of obtaining underground data should be considered/ investigated.

Chapter 3: Developing a Localised Benchmarking Methodology

3.1 Preamble

The objective of this study is to develop a methodology to identify underground compressed air inefficiencies that would serve towards improving the efficiency of the entire compressed air network. This chapter focuses on the development of the methodology by utilising the knowledge obtained from Chapter 1 and Chapter 2. Figure 8 illustrates an overview of the developed methodology.
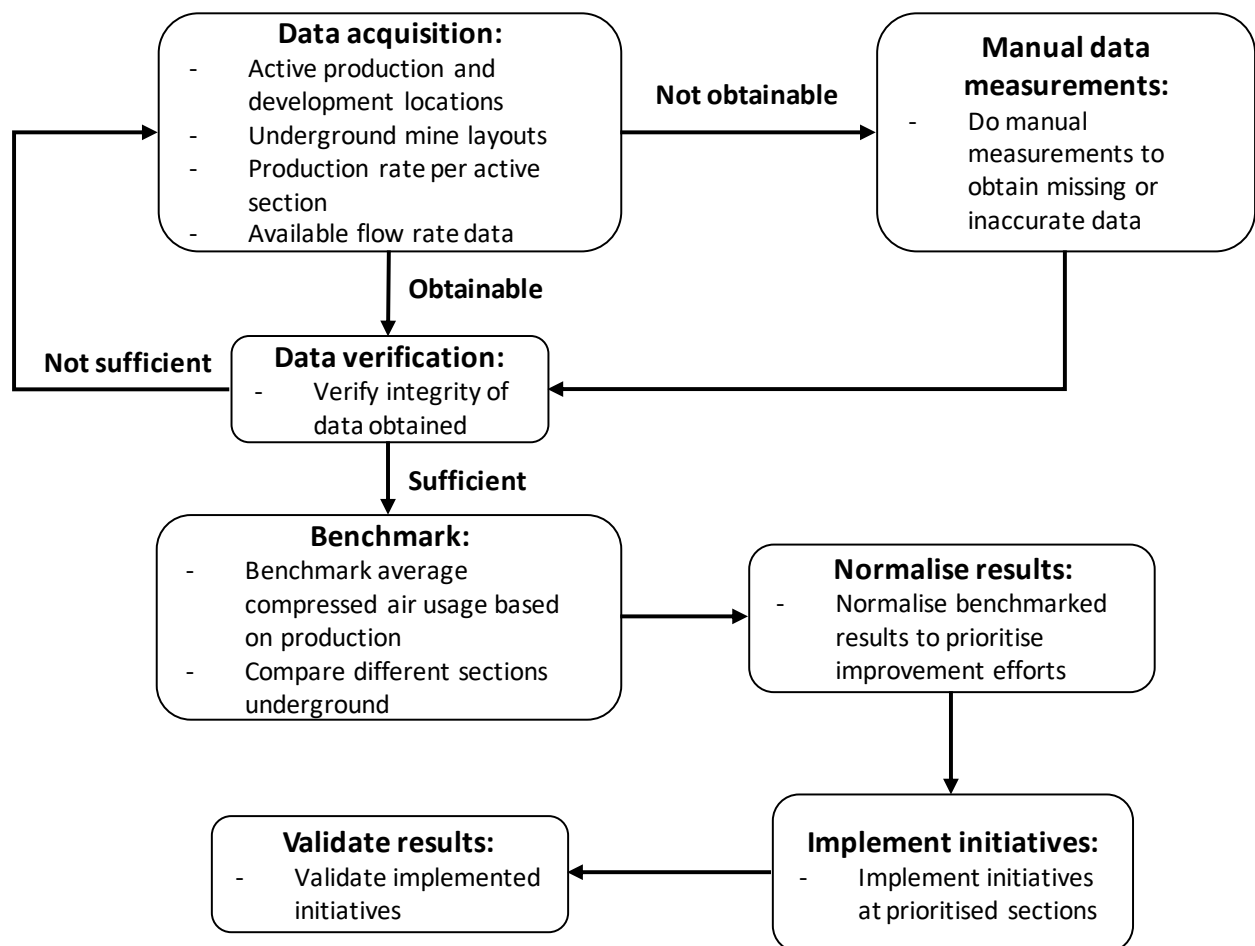

Figure 8: Overview of developed methodology

3.2 Data acquisition and verification procedure

3.2.1 Background

Obtaining accurate data is an essential prerequisite for all improvement efforts [4], [39]. Thus, data acquisition is the first step of the developed benchmarking methodology. The underground mine layouts of all active mining sections should be acquired and analysed to determine strategic locations where data should be collected for benchmarking. If smaller sections are benchmarked, inefficiencies can be allocated to smaller sections. However, more data is required if smaller sections are benchmarked, which can be problematic if limited data acquisition instrumentation is installed at the mine.

Underground scales are used to measure the ore mined per underground section. Trains that collect ore from the various sections drive over the scales to measure the amount of ore collected in tonnes. The bonuses of mine operators are dependent on the amount of ore that is produced by their section [8]. Therefore, these scales are calibrated regularly and are assumed to be accurate. Thus, the production data is readily available and should be obtained from the mine.

Permanently installed flowmeters are typically used to determine the compressed air usage per unit time [39]. In Chapter 2.4.1 it was found that most mines do not have the required instrumentation installed for sufficient benchmarking [12]. Furthermore, existing portable flowmeters are not sufficient to use in underground mines. To mitigate the impracticalities associated with conventional flowmeters, a data procurement procedure is developed that requires less time, less money and fewer resources than conventional data procurement methods [46].

The pressure drop over a pipeline is related to the flow rate through the pipeline. The relationship between pressure loss and flow rate is evaluated in the following section to determine the possibility of calculating flow rate with pressure measurements.

3.2.2 The relationship between pressure and flow rate

The relationship between pressure loss and airflow velocity in a pipeline is described by the Darcy–Weisbach equation.

Equation 5: Darcy–Weisbach [20]

$$DP = f\left(\frac{L}{D}\right)\left(\frac{pV^2}{2}\right)$$

Where:

DP   Pressure drop [Pa]

f   Friction factor [–]

L   Pipe length [m]

D   Hydraulic diameter [m]

p   Fluid density [kg/m³]

V   Average velocity [m/s]

The Darcy–Weisbach equation (Equation 5) does not clearly show the relationship between pressure loss and airflow velocity since the friction factor is also a function of air velocity. According to Joubert, the compressed air flow in a mine compressed air network is turbulent [11]. Turbulent airflow in a round pipe section corresponds to a Reynolds number larger than 10 000 [57]. The Swamee–Jain equation can be used to calculate the friction factor for turbulent flow (Equation 6).

Equation 6: Swamee–Jain [20]

$$f = 0.25\left[log10\left(\frac{e}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^{-2}$$

Where:

f   Friction factor [–]

e   Surface roughness [m]

D   Hydraulic diameter [m]

Re   Reynolds number [–]

The Swamee–Jain equation (Equation 6) indicates that the friction factor is a function of the Reynolds number, which is a dimensionless parameter. The Reynolds number is also a function of airflow velocity, which is defined by Equation 7.

Equation 7: Reynolds [20]

$$Re = \frac{\rho V L}{\mu}$$

Where:

ρ Density of air [kg/m^3]

V Average velocity [m/s]

L Pipe length [m]

μ Dynamic viscosity of the fluid/gas [Pa·s]

In summary, Equation 5, Equation 6 and Equation 7 show that pressure drop is a function of airflow velocity as well as a function of the friction factor. The friction factor is a function of the Reynolds number, which is also a function of airflow velocity. The relationship is symbolically illustrated as follows:

$$DP(V, f(Re(V)))$$

Therefore, the relationship between pressure drop and airflow velocity is non-linear and complex. It should be noted that the velocity of air can be converted to flow rate with Equation 8 to obtain the relationship between airflow rate and pressure loss.

Equation 8: Flow rate conversion [12]

$$Q = VA$$

Where:

Q Volume flow rate [m^3/s]

V Average velocity [m/s]

A Area [m^2]

Although the actual relationship between airflow rate and pressure loss is complicated, it can be assumed that the relationship is dominated by a power factor as can be seen in the Darcy–Weisbach equation (Equation 5). This assumption is verified by the regression analysis below.

Regression analysis is typically done to determine the relationship between two independent variables [58]: in this case, the variables are flow rate and pressure loss. All other variables are kept constant for the analysis as would typically be the case for a pipe section. Figure 9 illustrates two analyses, one where the friction factor is a function of the Reynolds number (blue line) and one where the friction factor is kept constant (orange line).

The regression analysis indicates that there is a quadratic power relationship between pressure drop and flow rate if all other variables including temperature (T), density (ρ), diameter (D), surface roughness (e), pipe length (L) and dynamic viscosity (μ) are kept constant. These variables will typically stay constant for a pipe section. It is therefore possible to calculate the flow rate through a pipe section with pressure measurements from first principles.
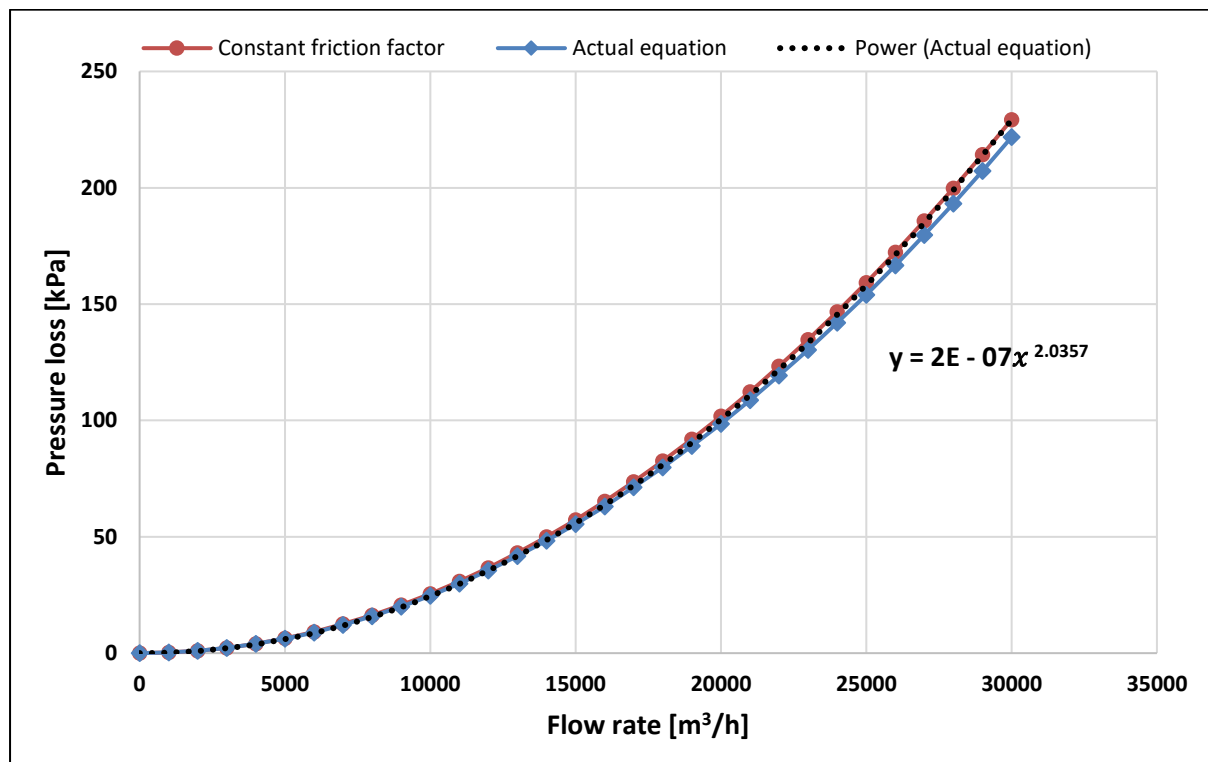

The equation shown on the chart:

$$y = 2E - 07x^{2.0357}$$

Figure 9: Flow rate and pressure loss regression analysis

When the friction factor is kept constant (not a function of flow rate) as shown by the orange line in Figure 9, only a small deviation is observed from the original equation (3%), which is shown in blue. This phenomenon is further supported by the trend line of the actual equation (shown as a black dotted line in Figure 9), which indicates a quadratic relationship between pressure drop and flow rate as can be seen from the dominating factor in the Darcy–Weisbach equation. Therefore, to simplify the process of calculating the flow rate from pressure loggers, the friction factor can be kept constant.

The friction factor of every pipe section is different and cannot be calculated without the flow rate. Therefore, three pressure loggers should be used per pipe section to determine the value of the friction factor. The middle-pressure logger data is used to calibrate the resistance in the pipeline. This allows an accurate representation of surface roughness, obstructions and bends in the pipeline. If the pipeline is modelled correctly, a more accurate flow rate can be obtained. By inserting three pressure loggers, the pressure difference over all three loggers can be used for calculations. The procedure for calculating the flow is explained below.

Three pressure loggers are installed to obtain pressure data at three different locations over a pipe section. Most parameters should stay relatively constant over the entire pipe section including airflow rate, friction and pipe diameter. The variables that are not constant over the entire pipe section are indicated in Figure 10.
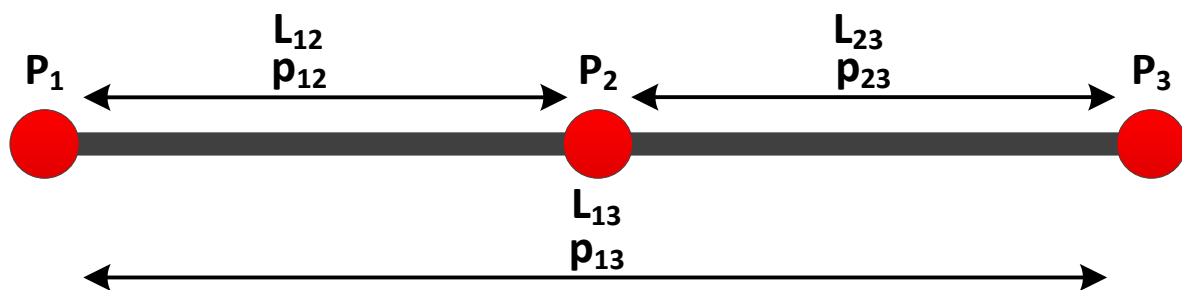

Figure 10: Pressure drop variables

The symbols presented in Figure 10 are abbreviated in the equations that follow. Figure 10 illustrates that the density and length of the pipe sections separated by the middle logger will not be the same. All other applicable variables can be considered constant through the entire pipe section.

To calculate the density in each section, the ideal gas law can be used. The ideal gas law was introduced in Chapter 2.3 of this study. Pressure, temperature and the gas constant are required to calculate the density. Because pressure varies through a pipe section, the pressure at the end points is averaged as an appropriate input for the calculation. This is common practice in fluid dynamics studies if a variable is only known at the end points [57].

To solve the problem, the Darcy–Weisbach equation (Equation 5) and ideal gas law (Equation 4) are implemented on the first and last pipe section. Two equations are therefore available that include the pressure calculation from Point 1 to Point 2 (Equation 9) and from Point 2 to Point 3 (Equation 10).

Equation 9: Pressure loss from Point 1 to Point 2

$$P_1 - P_2 = f\left(\frac{L_{12}}{D}\right)\left(\frac{(P_1 + P_2)V^2}{4}\right)$$

Where:

P_1 Pressure at Point 1 [Pa]

P_2 Pressure at Point 2 [Pa]

f Friction factor [–]

L_{12} Pipe length from Point 1 to Point 2 [m]

D Hydraulic diameter [m]

V Average velocity [m/s]

Equation 10: Pressure loss from Point 2 to Point 3

$$P_2 - P_3 = f\left(\frac{L_{23}}{D}\right)\left(\frac{(P_2+P_3)V^2}{2}\right)$$

Where:

P_2 Pressure at Point 2 [Pa]

P_3 Pressure at Point 3 [Pa]

f Friction factor [–]

L_{23} Pipe length from Point 2 to Point 3 [m]

D Hydraulic diameter [m]

V Average velocity [m/s]

Two unknowns are present, namely, the airflow velocity and the friction factor of the pipeline. It can be assumed that the unknowns stay constant through both pipe sections. The equations can therefore be solved numerically to obtain the airflow velocity. The airflow velocity can then be converted to flow rate with the flow rate conversion equation previously presented. The values of other variables contained in Equation 9 and Equation 10 can be obtained from the data procurement procedure explained in Chapter 3.2.3.

3.2.3 Procurement procedure

When permanent measuring instrumentation is not installed, manual data measurements are necessary to obtain the required data for benchmarking. The procurement procedure includes installing three pressure loggers in each mine section that does not measure compressed air flow. An illustration is shown in Figure 11. The illustration is a top view of a single level underground. The blue line indicates the compressed air supply pipe and the grey lines indicate the underground walkways.
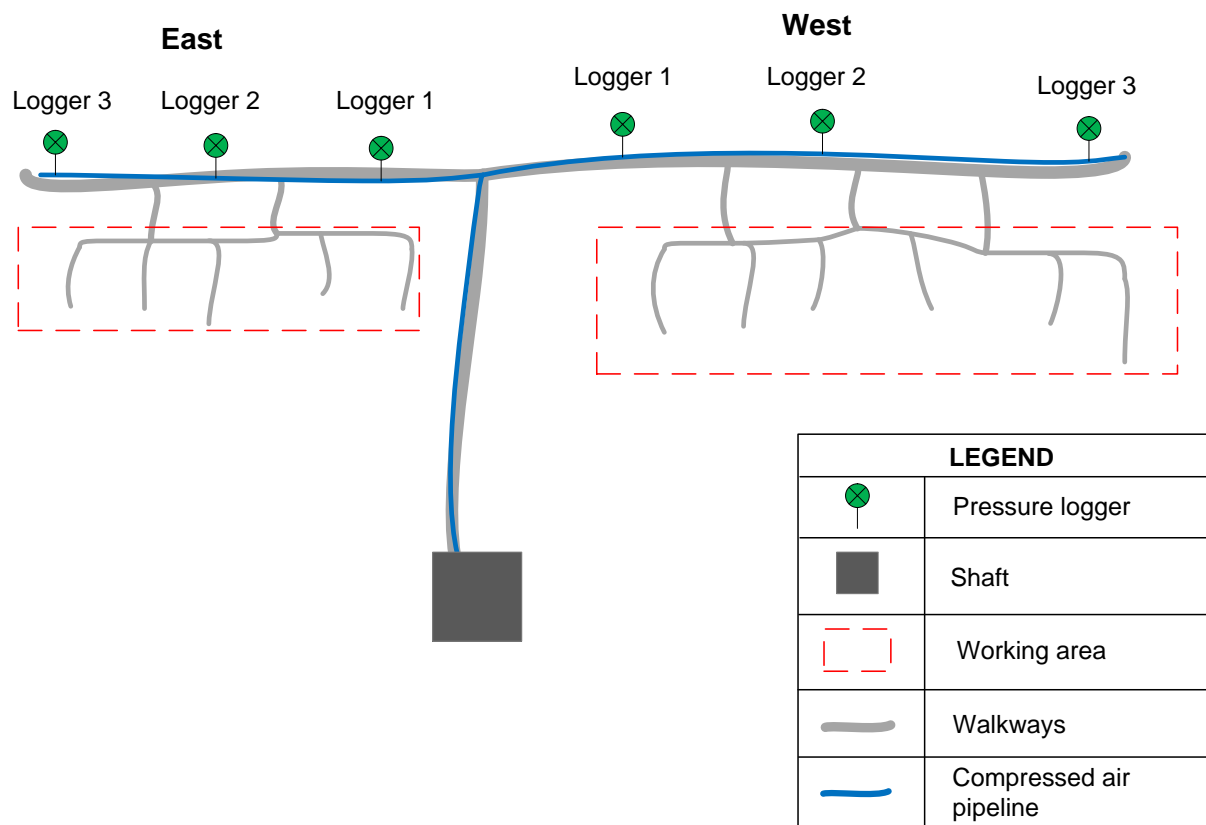
Figure 11: Simplified top view of a level on a typical deep-level mine

In Figure 11, there is no permanent instrumentation installed at the start of the level, and the flow to the east and west side of the level needs to be determined. The first pressure logger (Logger 1) is installed at the beginning of the mine section. The last pressure logger (Logger 3) is installed at the end of the mine section. Also, the middle logger (Logger 2) is installed approximately in the middle between the first and third loggers. Three loggers are therefore installed on each mining section of which the compressed air consumption needs to be determined. The pipe diameter should be measured and noted throughout the installation. The exact position of the installed loggers should also be noted to determine the pipe lengths between loggers.

Some of these levels can be up to 10 km long. It would be impractical to measure the lengths between installations manually. A more practical way to determine the lengths is to note the location of the installation with some reference point. For example, a box front number or working area number. These reference points can then be used to determine the exact lengths between installations with a digital layout that can be obtained from the mine's drawing office.

The compressed air demand changes throughout the day. Therefore, the loggers need to be installed for at least 24 hours so that the entire compressed air demand characteristics can be captured in the obtained data. Pressure loggers can be installed on more than one section at a time. This will depend on the number of pressure loggers and auditors available. By installing loggers at multiple sections at a time, the noise obtained from slight deviations in day-to-day compressed air demand can be limited. Planning should be done beforehand to ensure that resources are used to their maximum potential. Obtaining underground layouts and information of active work areas would greatly aid in preparation for the data measurements.

3.2.4 Data verification

To verify if the pressure loggers can be used accurately to calculate the airflow to different sections, the results should be compared with the measurements of an accurate flowmeter. Insertion-type flowmeters are considered the most accurate instrumentation used to measure compressed air flow [46].

A portable insertion flowmeter should be used to measure the airflow in conjunction with installed pressure loggers. Because of the challenges associated with installing these flowmeters in underground mines, it is not practical to install the flowmeters for the entire duration that the pressure loggers are installed. However, because the flowmeter measurements are only for verification purposes, only a couple of hours of data is required for comparison.

The airflow rate calculated by the pressure data should be compared with the corresponding flowmeter measurements. A close relation and a small absolute difference between the calculated and measured flow consumption serves as verification that the developed procedure is an accurate method for calculating flow rate through a pipe section.

Once all the data has been verified as accurate and sufficient, the benchmarking process can continue. However, if the data is not sufficient and reasonable assumptions cannot be made to substitute missing or inaccurate data, the data should be recollected from the start. Recollection of data should be done for different time intervals or from different sources to ensure that the data will not be insufficient again.

3.3 Developing a localised benchmarking and normalisation methodology

Once accurate flow rate and production data has been obtained from the various sections, a preliminary local benchmarking procedure should be performed. The preliminary benchmarking procedure includes calculating the ratio of compressed air consumption to production output in m³/h per tonnes produced for each section.

In Chapter 2.3 it was established that there is a strong linear correlation between compressed air consumption and production output. Therefore, when the ratio of compressed air consumption (input) to production output is compared for different sections, insight can be gained into the compressed air efficiency of each section. Sections with a poor input-to-output ratio would be considered as inefficient users of compressed air.

Thus, the preliminary benchmarking phase can be used to determine where inefficiencies are in the compressed air network. However, the objective of this study is not to locate inefficiencies that degrade the performance of a section, but rather to locate inefficiencies that degrade the performance of the entire compressed air network. For example, rectifying wastage of a section underground with a poor performance regarding input-to-output ratio, but that does not use a considerable amount of compressed air, would have little effect on improving the efficiency of the compressed air network. The more unnecessary airflow consumption can be reduced, the higher operational efficiency improvement can be achieved.

The preliminary benchmarking results should, therefore, be normalised to ensure that improvement efforts can be directed appropriately. Equation 11 was developed to normalise the benchmarking results. This gives a better indication of which section inefficiencies would provide the most opportunity for overall operational efficiency improvements.

Equation 11: Developed section indicator

$$Section_{indicator} = \frac{Consumption}{Production} \times \left(\frac{C_{factor} + P_{factor}}{2}\right)$$

Where:

$Consumption$	$Section\ flow\ rate\ [m^3/h]$
$Production$	$Section\ production\ [tonnes]$
C_{factor}	$\dfrac{Section_{consumption}\ [m^3/h]}{Total_{consumption}[m^3/h]}$
P_{factor}	$\dfrac{Section_{production}[tonnes]}{Total_{production}[tonnes]}$

The average flow rate and average production ratio are used for preliminary benchmarking to identify inefficiencies present in the network. Equation 11 normalises the ratio of input to output by multiplying by the average of the C_{factor} and P_{factor}.

The section indicator ensures that benchmarking can be done to identify inefficiencies that influence the entire compressed air network. This is done by taking the amount of air usage and not just the efficiency of air usage per section into account. The higher the indicator value, the more scope can be identified for operational improvement efforts.

It should be noted that normalisation and grouping techniques used in previous studies are not necessary. This is because variable energy governing factors stay relatively constant if benchmarking is done on different sections of the same mine. For example, ambient temperature and technology will not vary considerably from one section to the next.

3.4 Verification and validation process

The developed section indicator provides a tool to prioritise mine sections with inefficient compressed air usage that could be rectified to improve the efficiency of the

entire compressed air network. To verify if the indicator prioritises sections correctly, improvement initiatives should be implemented on the entire underground mine. The results should then be compared with prioritised levels.

A detailed audit serves as an accurate method to identify improvement initiatives in a compressed air network [46]. It should be noted that conducting detailed audits of an entire underground network requires extensive time and resources. The audit is required to verify the benchmarking process; therefore, it should be conducted only once. The audit should be conducted in the context of identifying any inefficiencies present in the underground network to implement all possible improvement initiatives. If the results of the improvements correspond to the prioritised levels, then it is verified that the developed methodology can accurately prioritise improvement efforts.

Quantifying the results of the improved initiatives for comparison is unfortunately not straightforward. Varying production rates influence compressed air consumption [21]. If production has changed since the initial benchmarking, the consumption before and after improvements have been made is not comparable. Additionally, as previously mentioned, the consumption reduction per section does not translate into overall compressed air network improvements.

To ensure that the improvements made translate into overall efficiency improvements, the change in consumption per section should be compared with the entire mine's consumption as initially measured. The results of sections with considerable efficiency improvements but small consumption would then be incremental to the consumption of the entire mine. Also, to ensure that results are comparable even when production rates have changed, the results should be multiplied by the change of production. Literature suggests that production in mines is the primary driver of compressed air consumption [21] and that the amount of ore produced is proportional to the amount of air consumed [4].

It was determined through experimental results and theoretical calculations in Chapter 2.3 that there should be a strong linear correlation between compressed air consumption and production output in mines. Therefore, it can be assumed that when production output changes, the compressed air consumption changes proportionally.

Equation 12 was developed to compare the improvements to each section. The first factor of the equation presents the impact that the section consumption change has on the entire compressed air network. The second factor normalises the impact by multiplying it with the change in production to ensure that results before and after improvements made remain comparable. Comparing the normalised results with the prioritised levels serves as verification that levels are prioritised to improve the operational efficiency of the entire compressed air system.

Equation 12: Normalised improvement impact

$$N = \frac{Q_1 - Q_2}{Q_T} \times \left(1 + \frac{P_2 - P_1}{P_1} \right)$$

Where:

N	Normalised improvement impact [%]
Q_1	Section consumption before improvements [m³/h]
Q_2	Section consumption after improvements [m³/h]
Q_T	Initial consumption of entire mine [m³/h]
P_2	Section production after improvements [t/d]
P_1	Section production before improvements [t/d]

To verify if the improvements served towards operational efficiency improvements, a regression analysis should be done. A regression analysis is done to visualise and quantify the relationship between the input and output of a system. System efficiency is defined as the ratio of useful output to input; therefore, a regression analysis serves towards verifying if operational efficiency improvements have been made.

A better correlation between production and consumption of the different sections indicates that less air is lost or wasted. This can be quantified by the coefficient of determination when a linear best-fit line is incorporated into the regression analysis. The gradient of the linear best-fit line can then be used to determine the overall relationship of input to output of the system. Thus, the gradient can be used to

determine the efficiency improvements of the overall system. Significant improvements in the coefficient of determination and gradient of the linear best-fit line serve as verification that the methodology can be used to guide efforts that improves the operational efficiency of the compressed air network.

The developed methodology should be implemented on a different underground network for validation purposes. The methodology should be implemented to identify and prioritise sections that have the most potential for overall operational efficiency improvements. For validation, only the top prioritised levels should be investigated to determine possible improvement initiatives. By doing so, substantial time and resources will be saved compared with a comprehensive audit of the entire underground network. If significant improvements can be realised by implementing initiatives on the investigated levels only, it will serve as validation that the developed methodology can be used as a practical way to locate compressed air inefficiencies in an underground network.

3.5 Summary

The first phase of the benchmarking procedure is to obtain data. A practical data procurement procedure was developed for when data is not available from permanently installed instrumentation.

The relationship between airflow rate and pressure drop was investigated to develop a data procurement procedure with pressure loggers. It was found that there is a quadratically dominant relationship between pressure drop and flow rate through a pipe section. Thus, a procedure was developed whereby the flow rate could be calculated by measuring the pressure drop at different locations on a pipe section.

A local benchmarking methodology was developed that uses the obtained data to determine inefficiencies present in sections of the compressed air network. Normalisation was done to prioritise improvement opportunities so that improvements per section would lead to operational improvements of the total compressed air system. This was done to maximise the effect that section efficiency improvements would have on the power generation of the compressed air system and the production rate of the entire mine.

A verification process was developed to ensure that compressed air sections were prioritised accurately with the developed methodology. The verification process included comparing the results of implemented initiatives on the entire mine to the priorities of sections identified from the study. Normalisation methods were also developed to ensure that results could be compared appropriately even if production changes are present before and after initiatives are implemented.

Regression analysis was performed to verify that the improvements made per section translated into whole system operational improvements. Thus, the verification methodology consisted of ensuring that sections were prioritised accurately and that improvements made increased the operational efficiency of the compressed air system. The verification procedure ensures that the developed methodology can prioritise sections that would maximise power generation and production rate improvements.

A validation process was developed to ensure that the local benchmarking methodology is successful in aiding improvement efforts of the compressed air network. The validation process includes implementing the developed methodology exactly as intended for mine managers. This serves towards validating that the methodology is practical and effective to use.

Chapter 4: Validation of Developed Methodology

4.1 Preamble

In this chapter, the methodology developed in the previous chapter is applied to real South African platinum mines as case studies. The purpose of this chapter is to validate the developed benchmarking methodology and its application to deep-level mines. In addition to validating the benchmarking procedure, the developed data acquisition procedure is verified at the start of this chapter. The validation and verification process is done as follows:

1. Case Study 1: Verification
   a. Implement developed methodology on underground network to prioritise levels that should be investigated.
   b. Implement improvement initiatives on the entire underground network regardless of prioritised levels.
   c. Compare the results of the implemented initiatives to prioritised levels to verify that the levels were prioritised correctly.

2. Case Study 2: Validation
   a. Implement developed methodology on an underground network to prioritise levels that should be investigated.
   b. Investigate the top prioritised levels to implement improvement initiatives.
   c. Compare production output and compressed air consumption before and after improvements were made to validate the developed methodology.

4.2 Verification of data acquisition procedure

A deep-level platinum mine was used as a case study to verify the newly developed data acquisition procedure. The data acquisition procedure developed in Chapter 3.2 was implemented on an underground mine section with limited infrastructure. The section had a compressed air pipeline extending approximately 4 km. Pressure loggers were installed at three locations over the active pipe section. KIMO® pressure

loggers were used to obtain pressure data. These loggers are robust and easy to install. They have a maximum sensitivity of 10 kPa and a battery life of approximately two years. A KIMO pressure logger is presented in Figure 12.

Figure 12: KIMO pressure logger[4]

The data obtained was used to calculate the flow rate through the pipe section. The results were compared with measurements taken at the same time with a VA 500 flowmeter. The VA 500 flowmeter is a portable insertion mass flowmeter, which is considered to be one of the most accurate meters available [46].

The verification results are displayed in Figure 13. The measurements were only conducted for approximately one hour since they were only for verification purposes. The comparison was made from 09:18 to 10:24. The presented results show that there is a good correlation between the flow rate determined by the pressure loggers and the flow rate measured by the insertion flowmeter. The average absolute difference between the determined flow rates was less than 5.8% even though there was a total flow rate variation of 42% during the time that the flow rate was measured. The small

---

4 KIMO, "Technical data sheet", Route de Férolles, Paris. [Online]. Available: http://kimo-instruments.com/sites/kimo.fr/files/2018-03/FTang_Kistock_KCC-KPA-320_27-02-18.pdf [30 July 2018].

error can be due to the minimum measuring sensitivity of the pressure loggers used (10 kPa).
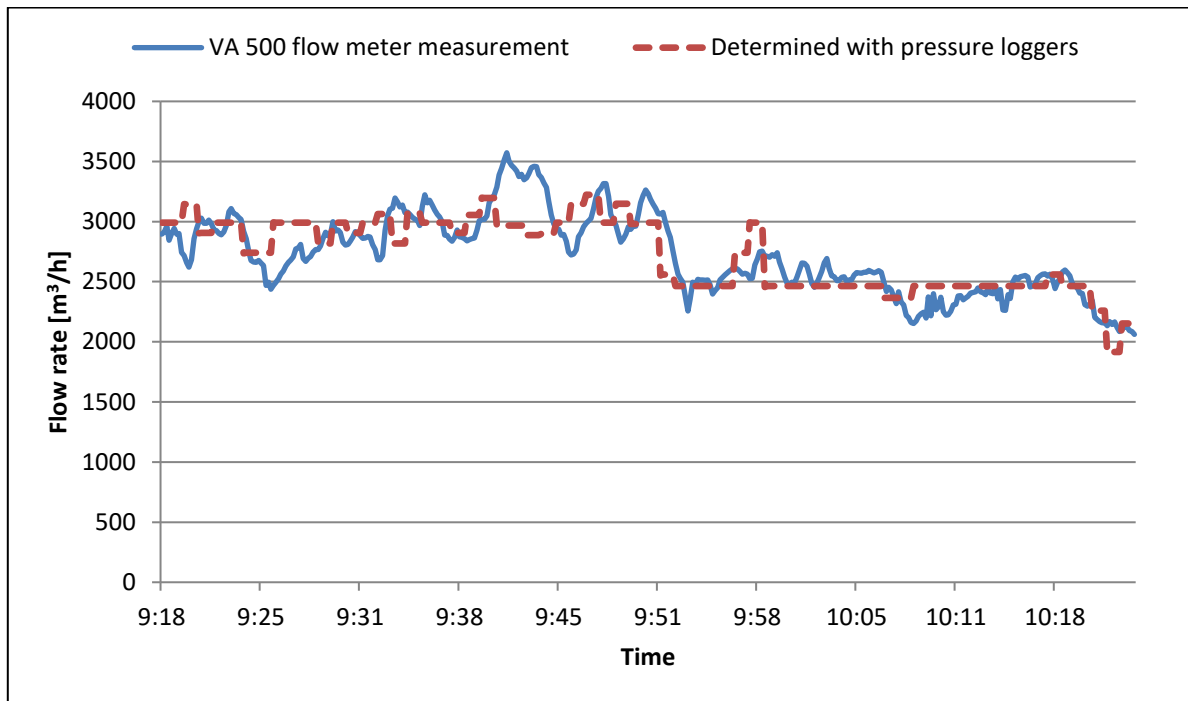

Figure 13: Manual data verification results

The low sensitivity of the pressure loggers is illustrated in the characteristics of the determined flow rate results. Although the calculated flow rate from the pressure loggers stayed constant for long periods of time, there were sudden and sometimes significant changes. This is an indication that the pressure loggers used to calculate the flow rate have a low sensitivity. However, for the benchmarking study, the magnitude and not the exact profile of the flow rate was essential. The magnitude was calculated accurately with the pressure loggers. It can thus be confirmed that pressure data can be used to calculate the flow usage to underground sections with reasonable accuracy, especially for benchmarking purposes.

4.3 Verifying methodology on Case Study 1

4.3.1 Site background

The underground compressed air network of a South African platinum mine was selected as the first case study. Due to confidentiality, the name of the mine is not disclosed in this report. The scope of the study was limited to the selected shaft's

underground network. A simplified layout of the underground compressed air network is illustrated in Figure 14.
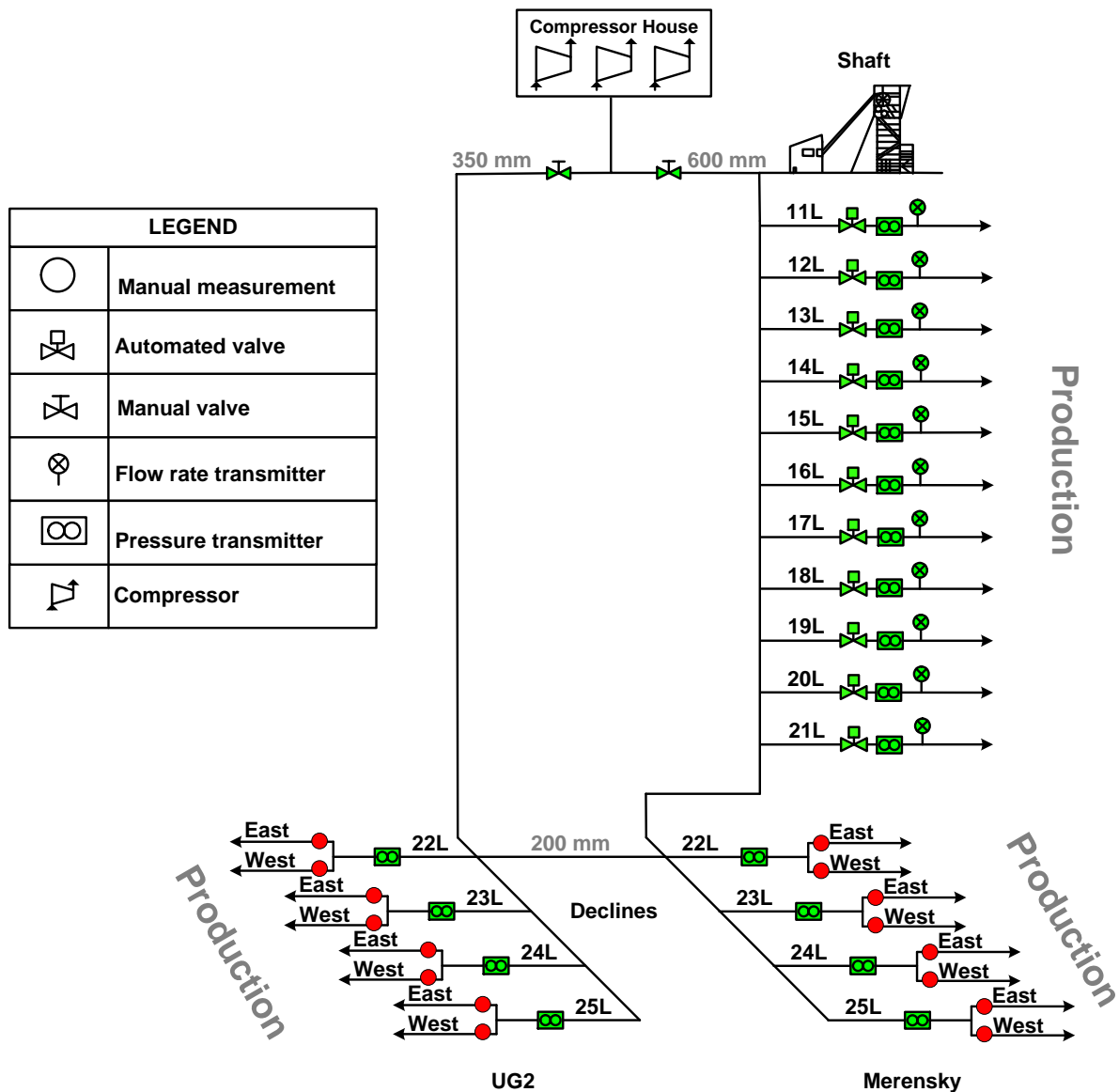
Figure 14: Compressed air network of Case Study 1

The compressed air pipeline extends from the surface to underground via a 600 mm and a 350 mm pipeline. These pipelines are connected on 22L underground to form a ring feed. The underground levels consist of the top levels (11L to 21L) and decline levels (22L to 25L). Each of the top levels has working instrumentation installed that includes an automatic control valve, pressure transmitter and flow rate transmitter.

The decline levels are separated into an Upper Ground 2 (UG2) and a Merensky side. The levels on the declines are split into an east and west side. The top levels and the

splits on the declines lead to working areas where most of the compressed air is used by rock drills [11].

It is important to note that the compressed air network is not connected on any level except as indicated in Figure 14. The network is also not connected to any other shaft and is therefore entirely isolated.

4.3.2 Data acquisition

4.3.2.1 Obtaining consumption data

The compressed air consumption data of the top levels was obtained from the permanently installed flowmeters. The accuracy of the installed flowmeters was verified with analysis of historical data and comparison of manual data measurements.

There is no instrumentation installed on the declines that can determine compressed air usage. Therefore, manual measurements were required to obtain data for benchmarking. The data procurement procedure developed in Chapter 3.2 was implemented on every half level of the declines. The locations where the data procurement procedure was implemented are illustrated with red circles in Figure 14.

Twelve KIMO pressure loggers and two auditors were used to conduct measurements at a total of 16 sections. As explained in Chapter 3.2.3, a total of three pressure loggers should be installed at every section for at least 24 hours to determine air consumption. Therefore, the measurements were limited to four sections per day for a total of four days. To conduct the same measurements with a conventional flowmeter, the meter would have to be installed at one section at a time for at least 24 hours. Therefore, the data was obtained at least four times quicker than using a conventional flowmeter.

4.3.2.2 Obtaining production data

The shaft used a tracking solutions company named Accutrak [59] to monitor and analyse the amount of transported ore underground. A system called Smartrail™ [60] uses radio frequency devices to tag each hopper, which is a wagon used underground to transport ore. A hopper data device (HDD) is installed on every locomotive and hopper underground [61]. The HDDs are radio frequency devices that give each hopper an identity. Box fronts are used to store ore before it is collected by passing hoppers (Figure 15). Each box front is installed with a beacon that has a unique ID.

When a hopper is used to load ore at a box front, a sensor on the door of the box front is triggered. The beacon containing the unique box front ID then sends a signal via radio frequency identification (RFID) to the HDD installed on the hopper that collects and stores information. When data is collected at the box fronts, it is referred to as the beacon and trigger system. The system is presented in Figure 15.
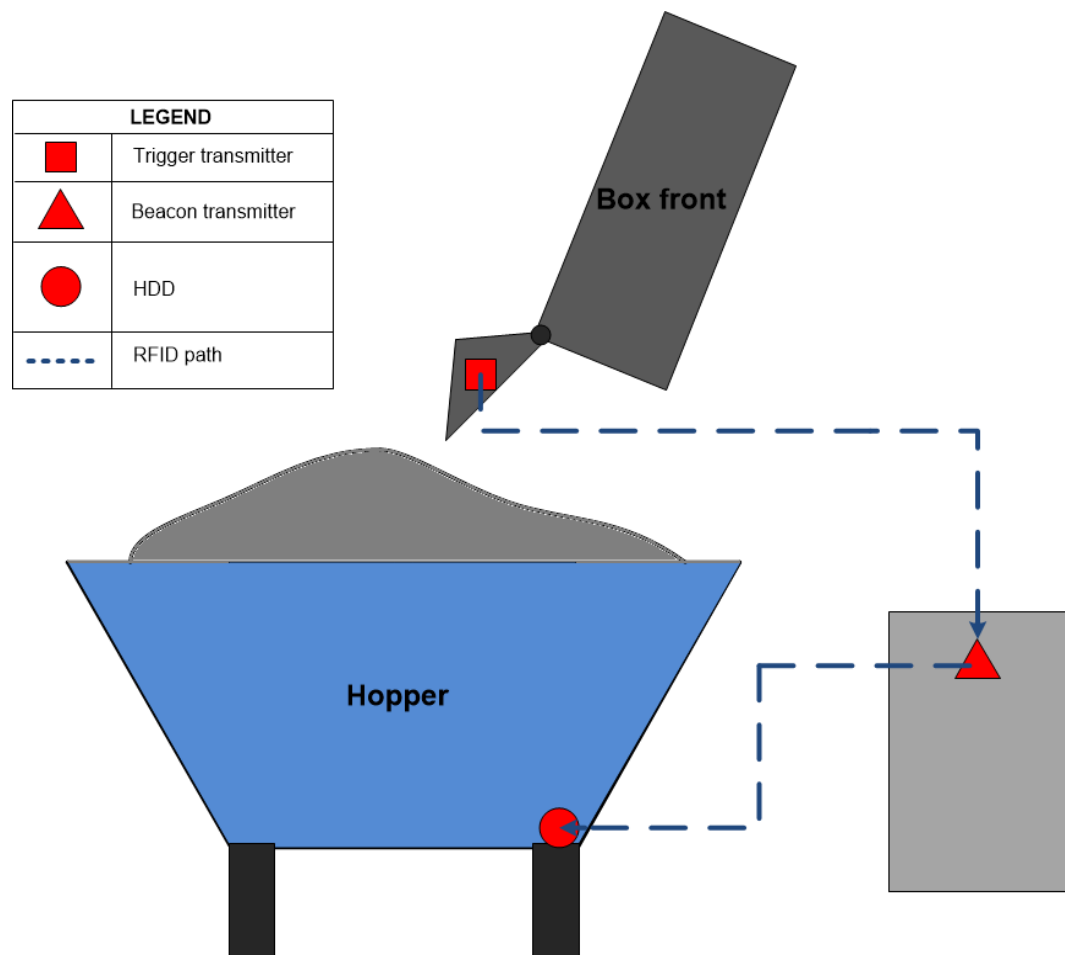
Figure 15: Beacon and trigger system (adapted from [61]**)**

A Smartrail weighbridge is in the main haulage close to the ore tips. Loaded hoppers are transported with locomotives from the box fronts to the ore tipping point. As a hopper crosses the weighbridge, its identity, place of origin and mass are recorded and sent to the surface where the data can be analysed in real time.

The mass of the ore is determined by load cells, which are installed at the weighbridge. Accutrak has a contractual obligation to ensure that the weighbridge takes accurate measurements. The load cells must be calibrated at least once every quarter [59]. For

this study, the production data was collected from the mine's Accutrak system. Because of their contractual obligation to provide accurate measurements, it was assumed that data obtained from Accutrak was accurate.

4.3.3   Benchmarking results

In Chapter 3 it was determined that preliminary benchmarking should be done to better understand the compressed air inefficiencies per section. For this study, it was decided, based on the available data and layout of the compressed air system, to benchmark the daily average compressed air consumption and production of every level underground. The manually obtained flow rate data per half level underground was summed to represent the consumption of each level; the same was done for the obtained production data.

The preliminary benchmark results are illustrated in Figure 16. The blue bars present the daily average production in tonnes per day. The red bars indicate the daily average compressed air flow rate in cubic metres per hour. The magnitude of the production is illustrated on the left-hand y-axis; the magnitude of the flow rate is illustrated on the right-hand y-axis. The preliminary results show that some levels have a reduced efficiency because they consume more compressed air for the number of tonnes they produce per day than other levels.
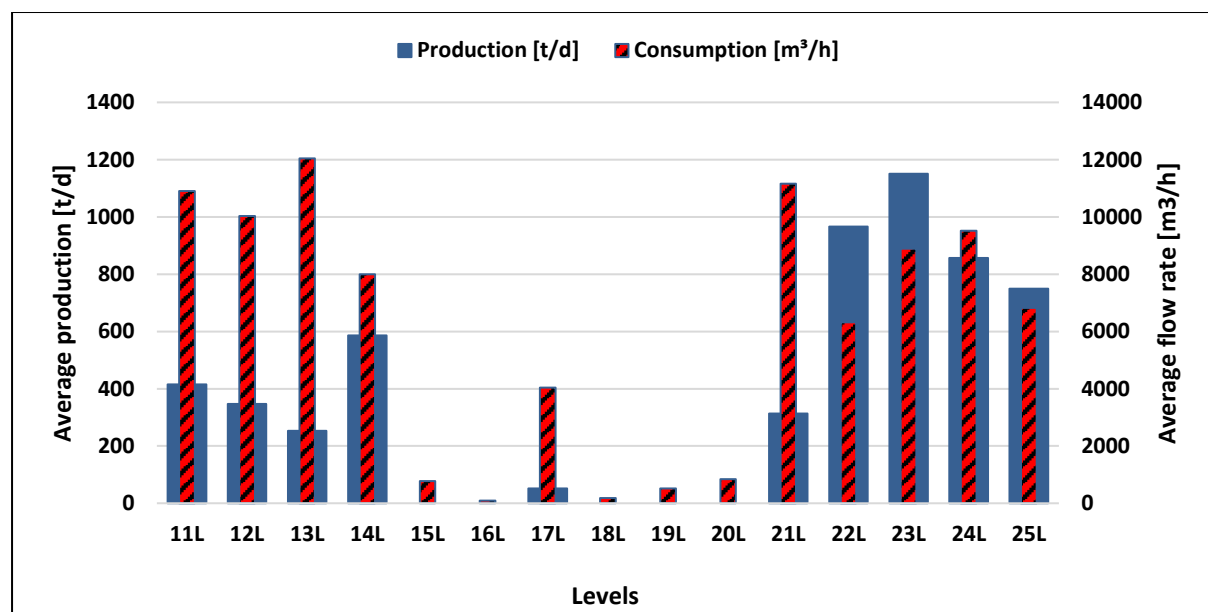

Figure 16: Preliminary local benchmark results of Case Study 1

The results show that, on average, the decline levels use compressed air more efficiently than the top levels. A possible explanation is the shorter length of the decline levels. The top levels typically extend from 6 km to 8 km whereas the decline levels only extend from 1 km to 3 km. Shorter pipe lengths mean less wastage and friction losses from the consumption measuring point to the rock drills used for production.

There are some sections, however, that have poor benchmarked ratios, but the amount of compressed air consumed does not make it worthwhile to investigate. To prioritise improvement efforts, the preliminary benchmarked results were normalised. The section indicator developed in Chapter 3.3 was used to normalise the results to give an indication of which section provides the most opportunity to improve the total compressed air network efficiency. The prioritised levels are displayed as a Sankey chart in Figure 17.
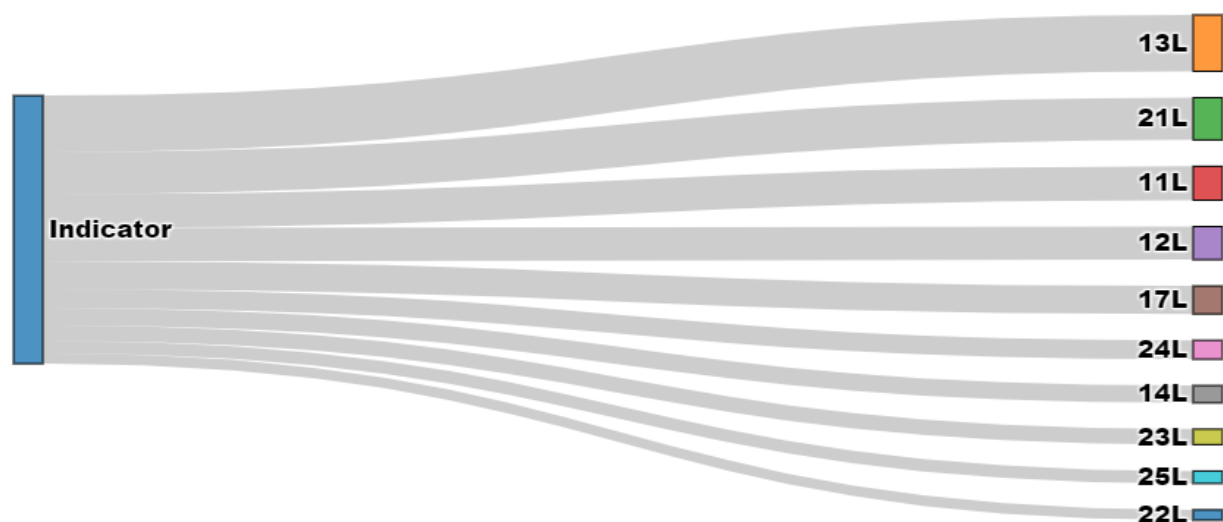
Figure 17: Normalised results of Case Study 1

The Sankey chart indicates the distribution of normalised results among different mining levels. The top level has the most significant distribution and is therefore the level that has the most potential for operational improvements. The normalised results indicate that 13L is the level that has the most scope to improve the operational efficiency of the compressed air network. This is based on the compressed air usage, the production rate of the level, and ratio of the production rate and air usage compared with other levels.

4.3.4 Verifying the methodology

Compressed air improvement initiatives were implemented on the entire underground mine to verify if the levels were prioritised correctly. A comprehensive audit was conducted to identify improvement initiatives. Comprehensive audits are presently the most effective method to detect inefficiencies in a mine's compressed air network. However, it becomes unpractical to conduct comprehensive audits when faced with a large and complex network. It took three auditors approximately three months to complete the full audit and identify the appropriate improvement initiatives. It is not practical to do such an audit on a regular basis because of the time and resources required. It thus illustrates the need to prioritise improvement efforts.

Some of the initiatives that were implemented were discussed in Table 2 of this report. It was found that the most considerable wastage was due to the compressed air supply to inactive sections of the mine. Inactive sections were supplied with compressed air because of negligence to close isolation valves to inactive sections and broken/faulty isolation valves.

Minor leaks were found in all the working places. These leaks are used for ventilation purposes as there is not sufficient ventilation of toxic gases in the work areas. The leaks in the work areas could therefore not be rectified. However, the amount of air loss through these leaks is limited and is assumed to be negligible regarding the total compressed air consumption.

Table 5 shows the audit findings, relevant improvement initiatives, the priority of the level that was determined by benchmarking, the total flow impact and the normalised improvement impact. The total flow impact is described as the monthly average change in consumption before and after improvements were made divided by the initial shaft consumption. The normalised improvement impact is the normalisation factor derived in Chapter 3.4, which is the total flow impact normalised by the change in production of the same period.

Table 5: Detailed audit results of Case Study 1 for verification

Level	Findings	Improvement initiative	Priority	Total flow impact	Normalised improvement impact – N
11L	Leaks in the main haulage / Supply to inactive section	Cut off supply to the inactive section	3	1.84%	2.51%
12L	Supply to inactive section / Leaks in working places	Cut off supply to the inactive section	4	1.60%	1.35%
13L	Supply to inactive sections / Development taking place	Cut off supply to the inactive sections	1	5.09%	8.20%
14L	No control of supply	Implement valve control	7	1.31%	1.45%
17L	Development taking place	No action	5	0.61%	0.38%
21L	Supply to inactive section / No control valves installed	Cut off supply to inactive section	2	7.36%	7.41%
22L	No control valves installed	No action	10	−0.14%	−0.11%
23L	No control valves installed	No action	8	0.04%	0.04%
24L	No control valves installed	No action	6	−0.28%	−0.33%
25L	No control valves installed	No action	9	−0.37%	−0.49%

In Chapter 3.4, the normalised improvement impact was deemed as the most appropriate way to quantify the impact that section improvements had on the system efficiency. The results indicate that there is a close relation to the prioritised levels and the normalised improvements. The most significant impact was made from improvements on 13L by cutting off the supply to inactive sections. The improvement results on 13L are displayed in Figure 18.

A significant reduction of approximately 8000 m^3/h can be seen from 09:30 on the day that the supply was cut off to the inactive section (green dashed line). The monthly average consumption of 13L reduced by 5769 m^3/h; thus, the improvement influenced the efficiency of 13L.
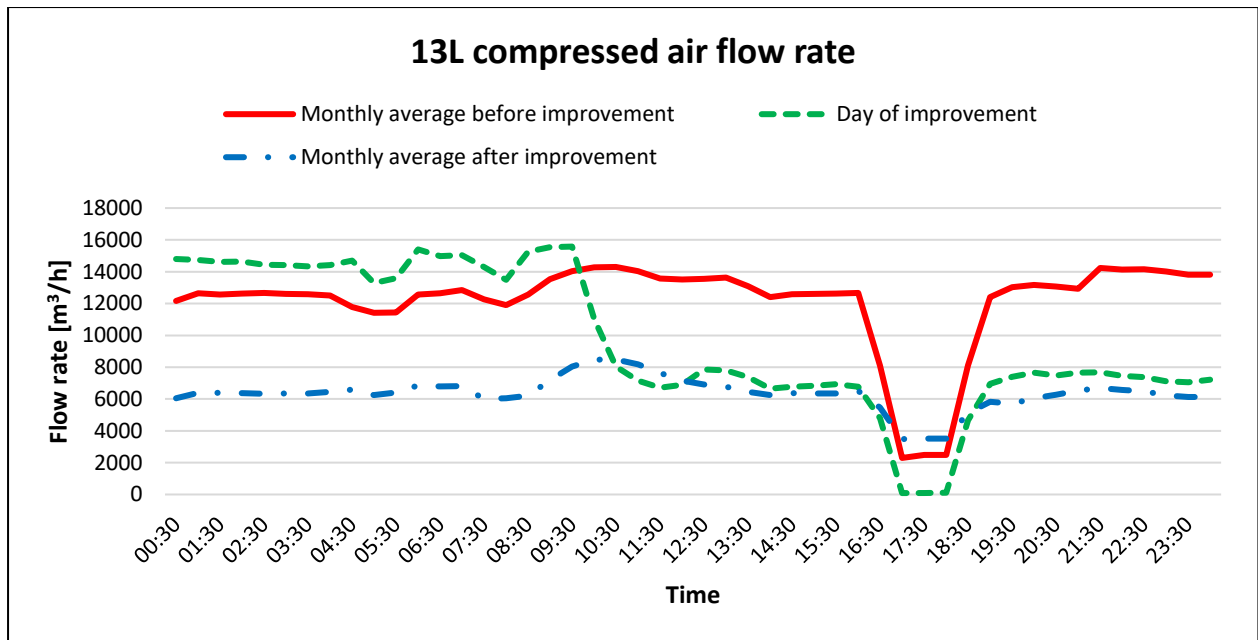
Figure 18: 13L improvement results

In addition to the results on 13L, shows that the top three prioritised levels correlate precisely to the most significant improvements made on the system. Upon further investigation, it was found that 80% of the total reduced compressed air consumption that was achieved could be allocated to the top three prioritised levels. Therefore, most of the improvement results could have been achieved by investigating the top three prioritised levels. The close relation of the improvements made from implemented initiatives and the prioritised levels serves as verification that the levels were prioritised accurately.

The regression analyses presented in Figure 19 and Figure 20 illustrate the effect that the implemented improvements had on the operational efficiency of the compressed air system. The analyses are regressions of the average production vs. the average consumption before and after inefficiencies were improved on every level. Data points allocated near the bottom-right of the figures are considered inefficient users of compressed air. Data points allocated near the top-left of the figures are considered efficient users of compressed air. The top three prioritised levels are indicated in Figure 19 and Figure 20 to highlight the considerable efficiency improvements made by these levels.
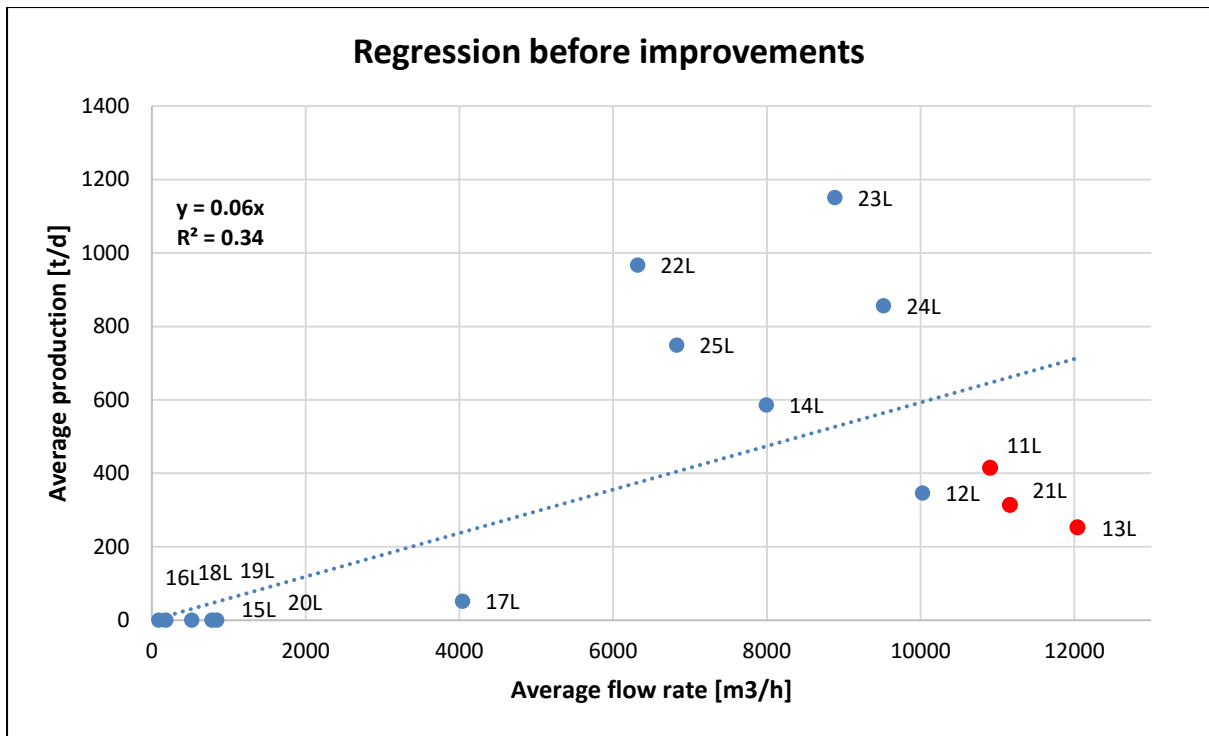
Figure 19: Regression analysis before improvements on Case Study 1

Figure 20: Regression analysis after improvements on Case Study 1

For an effective system, there should be a clear correlation between the input and output of the system. In Chapter 2.3 it was derived that there should be a strong linear correlation between consumption and production. Therefore, the effectiveness of the system was quantified by inserting a linear best-fit line through the data points.

The closer the data points are to the best-fit line, the better correlation is found between the input and output of the system. This correlation is quantified by the coefficient of determination (R^2). The analysis shows that the coefficient of determination value nearly doubled after improvements were made. The improved correlation between input and output of the system is an indication that compressed air wastage has been reduced.

Additionally, the gradient of the best-fit line also improved, which indicates that the efficiency of the compressed air system has improved. Therefore, the improved efficiency and effectiveness of the overall system verify that the improvements made per section translate into overall system improvements. Thus, the improvements made per level served towards energy cost savings and production improvements of the mine.

4.4 Validating methodology on Case Study 2

4.4.1 Site background

In this section, the developed methodology is systematically implemented in a second case study for validation purposes. Case Study 2 also consists of an underground compressed air network of a platinum mineshaft, as was the case for the first case study. A simplified layout of the compressed air network is illustrated in Figure 21.

A compressor house containing multiple compressors is situated near the main shaft that supplies air to underground. Air is supplied underground with two pipelines that are 450 mm in diameter. One of the pipelines supplies compressed air to all the underground levels including the top (16L to 25L) and decline (26L to 31L) levels. The second pipeline ties in with the first after 25L and 28L to form a ring feed.

The compressed air network is completely isolated from other underground networks, and there are no ring feeds between levels other than what is indicated in Figure 21.
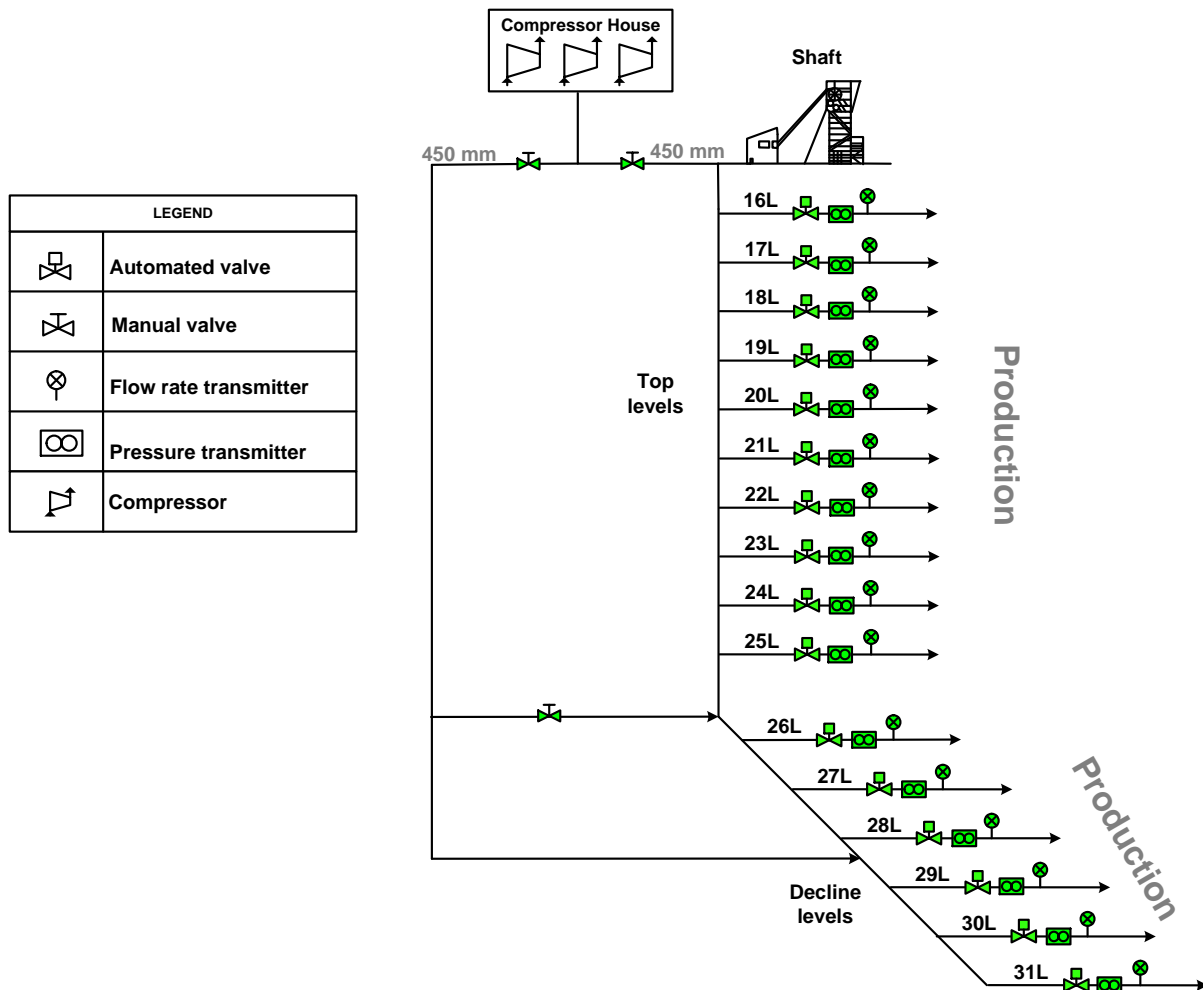
Figure 21: Compressed air network of Case Study 2

4.4.2 Data acquisition

Every level contains working compressed air instrumentation including automated control valves, flow rate transmitters and pressure transmitters. The flow rate transmitters on every level were used to obtain consumption data for benchmarking. The continuity and range of the data were inspected to verify that the obtained data was correct. Because all the levels had working instrumentation, there was no need to do manual data measurements. The Smartrail system was used to obtain production data on every level, same as the first case study.

4.4.3 Benchmarking results

The daily average consumption and production per underground level were compared with a preliminary benchmarking study. The results are displayed in Figure 22.
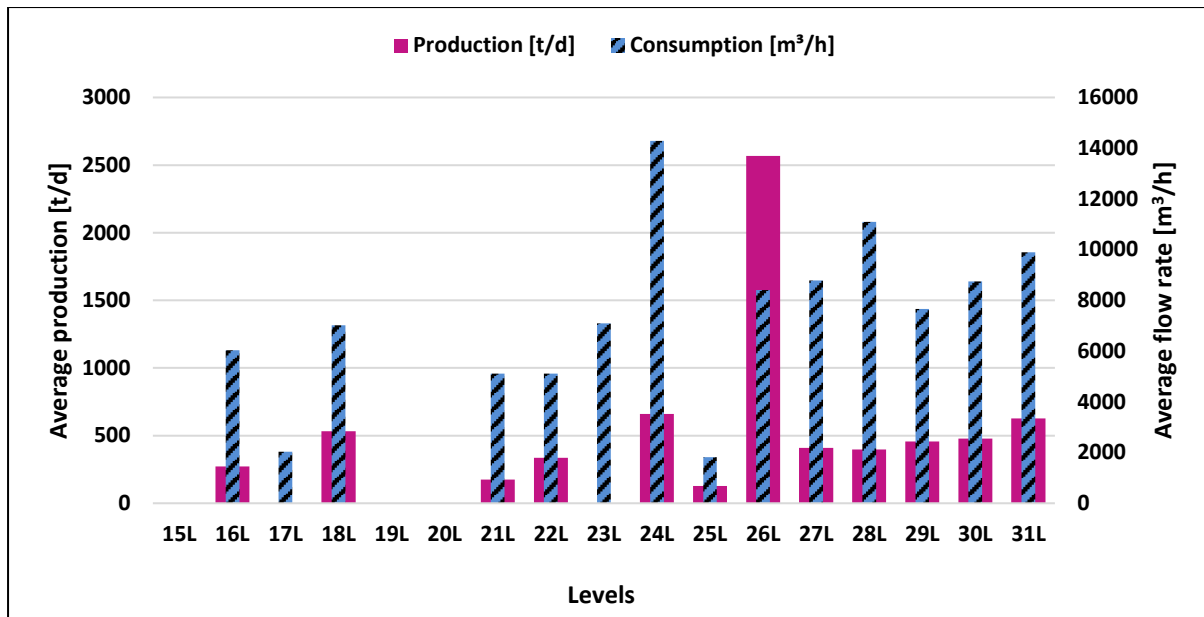
Figure 22: Preliminary local benchmark results of Case Study 2

The results indicate that most levels have a poor ratio of consumption to production output. 23L has no production output but uses a considerable amount of compressed air. The compressed air used by 23L compares to levels that produce a reasonable amount of ore. It was found that 23L was not under development and that there was no reason for 23L to use any compressed air. Therefore, 23L was flagged as a potential location to improve the operational efficiency of the compressed air network.

26L produces significantly more ore than other levels but consumes approximately the same amount of compressed air. This is an indication that other levels are not efficient users of compressed air and that there is a poor input-to-output ratio of the compressed air system. Therefore, there should be a significant opportunity to improve the operational efficiency of the compressed air network by rectifying wastage in the other levels.

The results were normalised as described in Chapter 3.3 to prioritise the levels. The levels were prioritised within the context of potential to improve the operational efficiency of the entire compressed air network. The normalised results are indicated as a Sankey chart in Figure 23.

Figure 23: Normalised results of Case Study 2

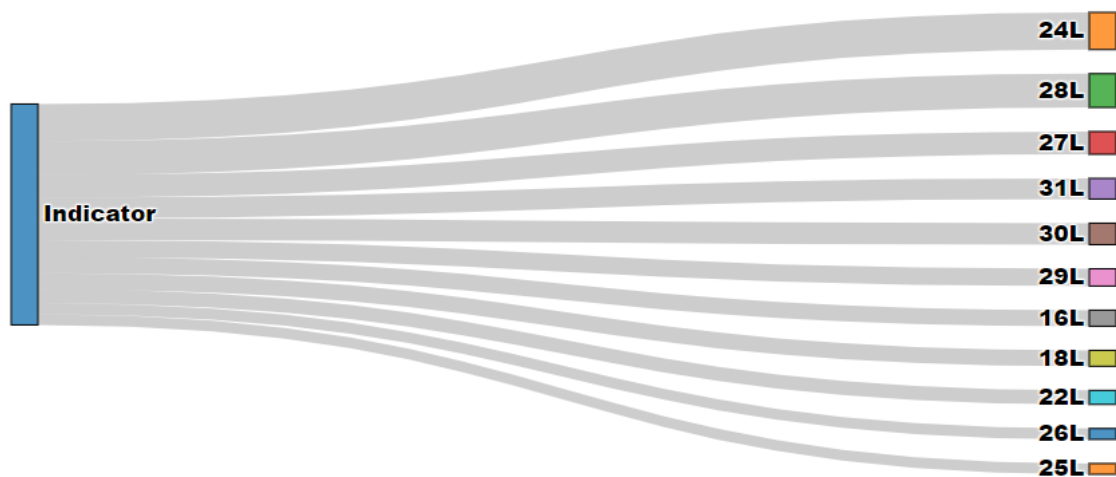The Sankey chart presents the distribution of normalised benchmarked results. The indicator developed in Chapter 3.3 was used to determine the priorities for improvement efforts. Note that the indicator used production and consumption data to determine the priorities. 23L did not have a production output; therefore, this and other levels (15L, 19L, 20L) do not feature in the normalised results. However, 23L was flagged as a priority in the preliminary benchmarked results.

4.4.4 Validation of methodology

To validate the methodology, the top two prioritised levels from the normalised results (24L and 28L) and the flagged level from the preliminary benchmarked results (23L) were audited. The audit took place to identify any inefficiencies present in the compressed air network. Inefficiencies include wastage due to leaks, insufficient valve control and supply to inactive levels, and losses that include unnecessary bends, deteriorated pipelines and insufficient pipe sizes.

It took approximately two weeks to conduct a comprehensive audit of 23L, 24L and 28L, which were the top three prioritised levels. An effort was made to rectify any inefficiencies found during the audit. The most considerable improvement was made on 23L where it was found that compressed air was supplied to multiple inactive sections. The supply to 23L was cut off to rectify the wastage of compressed air. Significant inefficiencies were also found on 24L and 28L. These inefficiencies included supply to inactive sections and significant leaks that were rectified.

The entire shaft's compressed air consumption and production output were compared before and after improvement initiatives were implemented. The average daily shaft compressed air consumption reduced from 103 105 m^3/h to 92 950 m^3/h, which is equivalent to a 10% reduction.

By analysing historical data, it was found that, on average, the compressors supply 9.58 m^3 of compressed air for every kW of power they consume. Therefore, the reduction in consumption is equivalent to 1060 kWh. If the power consumption is converted, it amounts to a cost of approximately R7.4 million per annum using 2018 electricity tariffs[5]. The average daily production has also increased from 7717 t/d to 9212 t/d, which is equal to a 19% increase.

The increased production and decreased consumption present a significant improvement in the operational efficiency of the compressed air network. It is important to note that the significant improvements were obtained by conducting audits of the top prioritised levels only and not the entire network. A substantial amount of time and number of resources were spared to obtain a significant amount of savings. Therefore, the results of Case Study 2 serve as validation that the developed methodology can be used as a powerful energy management tool to prioritise improvement efforts.

4.5 Discussion of results

Literature proved that there is a need to locate compressed air inefficiencies in an extensive underground mine without conducting an audit of the entire compressed air network. Local benchmarking was proposed as a solution to identify inefficiencies with minimal effort. The newly developed methodology was implemented in two case studies to verify that the method is accurate and to validate that the method solves the research problem.

For Case Study 1, improvement initiatives were identified through an extensive audit of the entire underground network, which took approximately three months to

---

[5] Eskom, "2018/19 Tariffs and charges", South Africa, Johannesburg. [Online]. Available: https://http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Pages/Tariffs_And_Charges.aspx [23 August 2018].

complete. The efficiency improvements made reduced the total shaft consumption while an increase in production rate was observed.

The reduced compressed air resulted in an electricity cost saving of R5.3 million per annum. The increased production is difficult to quantify in monetary value as these mines do not disclose their ore grade. However, an increase in production will be beneficial to the profitability of the mine.

The results of the improved compressed air network efficiency highlight the importance of compressed air energy management in an underground mine. At present, comprehensive audits are the only way for mine managers to identify compressed air inefficiencies, but it is becoming less practical as underground networks become more extensive and complex.

For verification, the prioritised levels from the newly developed methodology were compared with the results of the comprehensive audit. Even though the results of the improvements do not correlate precisely to the prioritised levels, the value of the developed methodology is evident when one considers that 80% of the reduced compressed air consumption was due to implemented initiatives at the top three prioritised levels.

While Case Study 1 was used to verify the methodology, Case Study 2 was used to validate the methodology. The newly developed methodology was systematically implemented in Case Study 2, and only the top prioritised levels were investigated. Implemented initiatives on these levels resulted in a 10% decrease in total shaft consumption while a 19% increase in production was observed. The reduced consumption translated into an electricity cost saving of approximately R7.4 million per annum.

Previously, no practical methods existed to identify localised compressed air inefficiencies on underground compressed air networks without spending an enormous amount of time and resources. The value of the study is evident when one considers that it took only two weeks to conduct the audit on Case Study 2 compared with the three-month comprehensive audit of Case Study 1.

It should be mentioned that Case Study 1 also has a slightly smaller compressed air network than Case Study 2. Therefore, theoretically it would have taken longer than three months to audit the entire underground network of Case Study 2. The results validate that the newly developed methodology provides a practical method to locate compressed air inefficiencies in an underground mine.

The developed methodology requires production output that is proportional to some measured input. Without the required data, manual measurements should be conducted or benchmarking will not be possible. The data procurement procedure developed in Chapter 3.2 was used to calculate the flow through the pipe sections where no permanent measuring instrumentation was installed. It was verified that the accuracy of the calculated flow rate is more than 94% than that of an insertion mass flowmeter. Obtaining the data with the developed procedure was at least four times quicker than with conventional flowmeters. Therefore, using pressure loggers instead of conventional flowmeters served as a more practical method to determine compressed air consumption. Pressure loggers are also significantly cheaper.

Thus, the developed methodology can be used on most mines to identify compressed air wastage even when faced with limited infrastructure. Furthermore, similar data procurement and local benchmarking strategies could be applied to various other compressed air networks where there is a correlation between compressed air consumption and an output.

Chapter 5: Conclusion

5.1 Summary

The South African mining industry is under strain because of rapidly increasing electricity costs. South Africa has the deepest mines in the world, which are continually extending to keep up with production targets as mining resources get depleted. As these mines mature, the efficiency of the compressed air network deteriorates at a significant pace to such an extent that the amount of air required to produce one tonne of ore has more than doubled in the past decade. Additionally, neglected compressed air networks contain a considerable number of losses and leaks, which adversely affect production.

Some initiatives have been implemented to reduce the consumption of compressed air in deep-level mines. However, improvement opportunities must be identified before implementation. Identifying these initiatives in an extensive and complex underground network is not a simple task. At present, limited energy management tools are available for underground compressed air networks.

Manual underground audits are presently the only way to identify some of the improvement initiatives underground. As mines mature, these comprehensive audits become unpractical because of the amount of time and number of resources they require. With the present strain on the profitability of mines, they cannot afford to neglect to maintain compressed air inefficiencies.

A local benchmarking methodology was developed to locate inefficiencies and to prioritise improvement efforts underground. The challenges associated with existing benchmarking studies were addressed in a detailed literature review. It was found that by benchmarking locally, varying energy governing factors do not play a role in the accuracy of benchmarking as these factors stay relatively constant for intra plant comparisons. Therefore, there was no need to implement complex grouping and mathematical manipulation or reasonable assumptions as required for previous studies on global benchmarking in the mining industry.

A KPI was developed for benchmarking as KPIs used in existing studies are not suitable on a localised level. The fundamentals of ore mining were investigated to determine appropriate input and output variables of the system. It was determined that the ratio of the compressed air consumption rate to the production rate would suffice as an appropriate KPI for local benchmarking comparisons.

Literature revealed that most mines have limited measuring instrumentation installed underground; therefore, manual data measurements would have to be conducted to collect the required data. A data procurement procedure was developed to obtain data when faced with limited infrastructure. Pressure loggers were used as an alternative method instead of costly portable flowmeters to determine the flow rate of compressed air through a pipe section.

It was verified that there is less than a 6% difference between the flow rate obtained from the conventional portable flowmeter and the data procurement procedure using pressure loggers. The developed measuring methodology serves as a more practical method to obtain data manually as the challenges faced by conventional flowmeters can be mitigated by using pressure loggers instead.

The developed benchmarking methodology was implemented on the underground compressed air network of two platinum mines as separate case studies. In both cases, the obtained consumption and production data was benchmarked on each underground level. Preliminary benchmarking presented sections with inefficient compressed air usage, but because section efficiency does not necessarily translate into overall system efficiency, the results were normalised.

Normalisation was done to take not only the level efficiency but also the magnitude of the compressed air consumption compared with other sections into account. By normalising the results, levels could be prioritised within the context of providing the most opportunity to improve overall compressed air efficiency that would lead to less generation cost and improved service delivery of the mine.

For Case Study 1, a comprehensive underground audit was conducted to locate inefficient usage in the underground mine network without considering the prioritised levels. An audit of this magnitude is not practical on a regular basis, which highlights

the need for an energy management tool to prioritise improvement efforts. However, for this study, improvement initiatives were implemented on every level where possible and the results were compared with the prioritised levels for verification purposes.

The results of Case Study 1 showed a good correlation between improvement results and the prioritised levels, especially for the top prioritised levels. Additionally, 80% of the total consumption reduction was obtained from the top three prioritised levels. The results verify that the newly developed methodology can be used to prioritise improvement efforts of an underground compressed air network with sufficient accuracy.

Regression analyses were done before and after improvements were implemented in Case Study 1 to illustrate the efficiency improvements of the entire underground compressed air system. The analysis showed that the relationship between the input and output of the system improved a considerable amount, which is an indication that compressed air wastage has been reduced. Additionally, the analysis showed the improved operational efficiency of the entire system. Therefore, the regression analysis verified that the improvements made per level translated into overall operational improvements of the system.

By improving the operational efficiency of the entire network, the power generation of the compressors was reduced to obtain an expected R5.3 million per annum cost saving while a slight increase in production was observed. The improvements made highlights the importance of energy management in an underground compressed air network. By utilising the proposed methodology, improvement efforts can be prioritised to save a significant amount of time and resources.

The proposed methodology was implemented in a second case study for validation purposes. The underground levels of Case Study 2 that had the most opportunity for overall operational efficiency improvements were prioritised with the newly developed methodology. This time, only the top prioritised levels were investigated to implement improvement initiatives. It took approximately two weeks to conduct the audit, which is approximately six times quicker than auditing the entire network with the same number of resources.

The implemented improvement initiatives resulted in a 10% reduction in shaft compressed air consumption, which amounts to an expected electricity cost saving of approximately R7.4 million per annum. A 19% increase in production output was observed. Therefore, a significant amount of operational improvement was achieved by auditing the top three prioritised levels only. Thus, it was validated that the proposed methodology can serve as a practical tool to prioritise improvement efforts of a deep-level mine compressed air system.

The newly developed methodology can have a significant effect on the way underground compressed air networks are maintained. Thus, to add to the existing knowledgebase the methodology was described in an article that was published in the journal Sustainable Production and Consumption. Compressed air inefficiencies can now be located in less time and with minimal resources. This will serve as a motivation for mine managers to audit underground sections more frequently, which will result in electricity cost savings and improved service delivery.

5.2 Limitations of the study and recommendations for further work

A shortcoming of the developed methodology is that it is limited to sections with a proportional relationship between input and output. The benefit of the study is therefore limited to active mining sections were production takes place. The methodology can therefore not accurately identify inefficiencies in sections with limited or no production output.

The preliminary benchmarking would, however, identify these sections and if the proportional consumption is considerable, one might consider investigating these sections. This was done on Case Study 2, where it was found that 23L consumed a considerable amount of compressed air without any production output. Additionally, normalisation techniques used in previous benchmarking studies could be used in such cases [4], [47], [48], [54].

These normalisation techniques consist of comparing the total generated compressed air power for benchmarking purposes. However, by using Equation 1 and Equation 2 in this report one would be able to convert the compressed air utilisation per section

to compressed air power generation per section. Therefore, with mathematical manipulation these previous studies can also be applied on a localised level.

Another shortcoming of the study is validating the methodology using a shaft network that is not interconnected with other shafts as is typical in the mining industry [12]. The addition of an interconnected network or ring feeds present between levels may yield different results. A further study is therefore required to determine if the proposed methodology can be applied to more complex compressed air networks that are interconnected underground with multiple shafts.

For such a study, the boundaries should be carefully considered. For instance, the usage of an isolated level will not be comparable to a level that is connected with another shaft. Additionally, underground compressed air ring feeds will not be comparable. In such a case, the ring feed should be considered as a collective section for comparison. To determine wastage, the data should be carefully analysed after initial benchmarking by considering the size and the nature of each benchmarked section.

The data procurement procedure developed for this study should apply to any pipe section containing any type of fluid or gas. For this study, the procedure was implemented on pipe sections ranging from 1 km to 8 km. If this procedure is conducted on shorter pipe sections, the pressure drop might be smaller than the maximum sensitivity of the pressure loggers (10 kPa).

Therefore, it is recommended that if this procedure is to be implemented on shorter sections; however, the minimum pipe length that would provide accurate results should first be determined. The minimum length can be determined by installing pressure loggers at different lengths in a pipe section. The data of the pressure loggers can be studied to determine what the smallest pipe length is where a pressure drop was observed. Alternatively, pressure loggers with a higher sensitivity can be used.

Reference List

[1] Z. Robinson, "Sustainability of platinum production in South Africa and the dynamics of commodity pricing," *Resources Policy*, vol. 51, no. July 2016, pp. 107–114, 2017.

[2] H. Langenhoven, "Mine SA 2017: Facts and figures pocketbook," Chamber of Mines of South Africa, Johannesburg, 2017, pp. 1–18.

[3] C. Cilliers, "Benchmarking electricity use of deep-level mine compressors," in *2016 Proceedings of the 13th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2016, pp. 1–6.

[4] C. Cilliers, "Benchmarking electricity use of deep-level mines," Ph.D thesis, School of Mechanical Engineering, North-West University Potchefstroom, 2016.

[5] C. Krogscheepers and S. J. Gossel, "Input cost and international demand effects on the production of platinum group metals in South Africa," *Resources Policy*, vol. 45, pp. 193–201, 2015.

[6] S. J. Bester, D. le Roux, and D. Adams, "The effect of compressed air pressure on mining production and energy demand," in *2013 Proceedings of the 10th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2013.

[7] J. I. G. Bredenkamp, L. F. van der Zee, and J. F. van Rensburg, "Reconfiguring mining compressed air networks for cost savings," in *2014 Proceedings of the 12th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2014.

[8] J. I. G. Bredenkamp, A. J. Schutte, and J. F. Van Rensburg, "Challenges faced during implementation of a compressed air energy savings project on a gold mine," in *2015 Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2015, pp. 23–29.

[9]   S. Cloete, D. le Roux, and T. Buhrmann, "Reducing compressed air wastage By installing new technology in underground mines," in *2013 Proceedings of the 10th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2013.

[10]   G. P. Heyns, "Challenges faced during implementation of a compressed air energy savings project on a gold mine," Ph.D thesis, School of Mechanical Engineering, North-West University Potchefstroom, 2014.

[11]   R. Joubert, "Cost and time effective DSM on mine compressed air systems," M.Eng. Dissertation, School of Mechanical Engineering, North-West University Potchefstroom, 2010.

[12]   C. J. R. Kriel, J. H. Marais, and M. Kleingeld, "Modernising underground compressed air DSM projects to reduce operating costs," in *2014 Proceedings of the 11th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2014.

[13]   J. H. Marais, "An integrated approach to optimise energy consumption of mine compressed air systems," Ph.D thesis, School of Mechanical Engineering, North-West University Potchefstroom, 2012.

[14]   P. Maré, J. I. G. Bredenkamp, and J. H. Marais, "Evaluating compressed air operational improvements on a deep - level mine through simulations," in *2017 Proceedings of the 14th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2017.

[15]   A. Schutte, M. Kleingeld, and J. Vosloo, "Various procedures to reduce a mine's compressed air usage," in *2011 Proceedings of the 8th Conference on the Industrial and Commercial Use of Energy, ICUE*, Cape Town, 2011, pp. 116–123.

[16]   M. Creamer, "Economist calls on South Africa to save pivotal gold- mining industry," *Mining weekly*, no. 3 Oktober, 2013.

[17] R. Saidur, N. A. Rahim, and M. Hasanuzzaman, "A review on compressed-air energy use and energy savings," *Renewable & Sustainable Energy Reviews*, vol. 14, no. 4, pp. 1135–1153, 2010.

[18] J. Vermeulen, "Simplified high - level investigation methodology for energy saving initiatives on deep - level mine compressed air systems," Ph.D thesis, School of Mechanical Engineering, University of Potchefstroom, 2017.

[19] H. Q. Shangai and A. McKane, "Improving energy efficiency of compressed air system based on system audit," Lawrence Berkeley National Laboratory, Berkeley, CA, 2008.

[20] E. W. McAllister, "Pipeline rules of thumb handbook: A manual of quick, accurate solutions to everyday pipeline engineering problems," in *Pipeline Rules of Thumb Handbook*, 6th ed. Boston, MA: Elsevier Science & Technology, 2014, pp. 606–614.

[21] R. Dindorf, "Estimating potential energy savings in compressed air systems," *Procedia Engineering*, vol. 39, pp. 204–211, 2012.

[22] H. P. Reddy, S. Narasimhan, S. M. Bhallamudi, and S. Bairagi, "Leak detection in gas pipeline networks using an efficient state estimator. Part-I: Theory and simulations," *Computers and Chemical Engineering*, vol. 35, no. 4, pp. 651–661, 2011.

[23] J. N. Da La Vergne, *Hard rock miner's handbook*, 3rd ed. Ontario: McIntosh Engineering, 2003.

[24] K. Paffel, "Air-System Leak," *Hydrualics & Pneumatics*, vol. 70, no. 11, pp. 22–27, 2017.

[25] M. Camber, "Compressed air demand : find and fix leaks first," *Plant Engineering*, vol. 68, no. 7, pp. 14–16, 2014.

[26] P. S. Murvay and I. Silea, "A survey on gas leak detection and localization techniques," *Journal of Loss Prevention in the Process Industries*, vol. 25, no. 6, pp. 966–973, 2012.

[27] S. Mekid, D. Wu, R. Hussain, and K. Youcef-Toumi, "Channel modeling and testing of wireless transmission for underground in-pipe leak and material loss detection," *International Journal of Distributed Sensor Networks*, vol. 13, no. 11, pp. 1–1, 2017.

[28] H. Jin, L. Zhang, W. Liang, and Q. Ding, "Integrated leakage detection and localization model for gas pipelines based on the acoustic wave method," *Journal of Loss Prevention in the Process Industries*, vol. 27, no. 1, pp. 74–88, 2014.

[29] S. Datta and S. Sarkar, "A review on different pipeline fault detection methods," *Journal of Loss Prevention in the Process Industries*, vol. 41, pp. 97–106, 2016.

[30] H. P. Reddy, S. Narasimhan, S. M. Bhallamudi, and S. Bairagi, "Leak detection in gas pipeline networks using an efficient state estimator. Part II. Experimental and field evaluation," *Computers and Chemical Engineering*, vol. 35, no. 4, pp. 662–670, 2011.

[31] W. Luís, V. Silva, L. Carvalho, O. Souza, and M. R. De Paula, "Mechanic and Energy," *REM - International Engineering Journal*, vol. 70, no. 4, pp. 421–428, 2017.

[32] A. Abdulshaheed, F. Mustapha, and A. Ghavamian, "A pressure-based method for monitoring leaks in a pipe distribution system: A Review," *Renewable and Sustainable Energy Reviews*, vol. 69, no. August 2016, pp. 902–911, 2017.

[33] A. Soldevila, J. Blesa, S. Tornil-Sin, E. Duviella, R. M. Fernandez-Canti, and V. Puig, "Leak localization in water distribution networks using a mixed model-based/data-driven approach," *Control Engineering Practice*, vol. 55, pp. 162–173, 2016.

[34] P. Cugueró-Escofet, J. Blesa, R. Pérez, M. Cugueró-Escofet, and G. Sanz, "Assessment of a leak localization algorithm in water networks under demand uncertainty," *IFAC-PapersOnLine*, vol. 28, no. 21, pp. 226–231, 2015.

[35] J. A. Goulet, S. Coutu, and I. F. C. Smith, "Model falsification diagnosis and sensor placement for leak detection in pressurized pipe networks," *Advanced Engineering Informatics*, vol. 27, no. 2, pp. 261–269, 2013.

[36] H. Nagasawa, H. Hibino, M. Hashimoto, and N. Kase, "Hybrid simulation method by cooperating between manufacturing system simulation and computational fluid dynamics simulation first report: Optimization for energy consumption per unit of production throughput considering compressed air feed," in *2017 IEEE International Conference*, Singapore, 2017, pp. 1616–1620.

[37] K. Bunse, M. Vodicka, P. Schönsleben, M. Brülhart, and F. O. Ernst, "Integrating energy efficiency performance in production management - Gap analysis between industrial needs and scientific literature," *Journal of Cleaner Production*, vol. 19, no. 6–7, pp. 667–679, 2011.

[38] W. Cai, F. Liu, O. Dinolov, J. Xie, P. Liu, and J. Tuo, "Energy benchmarking rules in machining systems," *Energy*, vol. 142, pp. 258–263, 2018.

[39] H. A. ElMaraghy, A. M. A. Youssef, A. M. Marzouk, and W. H. ElMaraghy, "Energy use analysis and local benchmarking of manufacturing lines," *Journal of Cleaner Production*, vol. 163, pp. 36–48, 2017.

[40] G. Festel and M. Würmseher, "Benchmarking of energy and utility infrastructures in industrial parks," *Journal of Cleaner Production*, vol. 70, pp. 15–26, 2014.

[41] E. Giacone and S. Mancò, "Energy efficiency measurement in industrial processes," *Energy*, vol. 38, no. 1, pp. 331–345, 2012.

[42] J. Ke, L. Price, M. McNeil, N. Z. Khanna, and N. Zhou, "Analysis and practices of energy benchmarking for industry from the perspective of systems engineering," *Energy*, vol. 54, pp. 32–44, 2013.

[43] G. May, I. Barletta, B. Stahl, and M. Taisch, "Energy management in production: A novel method to develop key performance indicators for improving energy efficiency," *Applied Energy*, vol. 149, pp. 46–61, 2015.

[44] D. Saygin, E. Worrell, M. K. Patel, and D. J. Gielen, "Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries," *Energy*, vol. 36, no. 11, pp. 6661–6673, 2011.

[45] T. Spiering, S. Kohlitz, H. Sundmaeker, and C. Herrmann, "Energy efficiency benchmarking for injection moulding processes," *Robotics and Computer-Integrated Manufacturing*, vol. 36, pp. 45–59, 2015.

[46] M. Koski, "Compressed Air Energy Audit 'The Real Story,'" *Energy*, vol. 99, no. 3, pp. 59–70, 2009.

[47] N. Wang, Z. Wen, M. Liu, and J. Guo, "Constructing an energy efficiency benchmarking system for coal production," *Applied Energy*, vol. 169, pp. 301–308, 2016.

[48] L. F. van der Zee, "Modelling of electricity cost risks and opportunities in the gold mining industry," Ph.D thesis, School of Electrical Engineering, North-West University Potchefstroom, 2014.

[49] I. G. Ital and S. O. Lu, "Addressing Plant Obsolescence with Digital Instrumentation and Control Systems," *Power Engineering*, vol. 120, no. 7, pp. 32–35, 2007.

[50] K. Lakshminarayan, S. A. Harp, and T. Samad, "Imputation of missing data in industrial databases," *Applied Intelligence*, vol. 11, no. 3, pp. 259–275, 1999.

[51] P. E. D. Love, J. Zhou, and J. Matthews, "Systems information modeling: From file exchanges to model sharing for electrical instrumentation and control systems," *Automation in Construction*, vol. 67, pp. 48–59, 2016.

[52] R. Squillante *et al.*, "Modeling accident scenarios from databases with missing data: A probabilistic approach for safety-related systems design," *Safety Science*, vol. 104, no. November, pp. 119–134, 2018.

[53] G. R. Ballantyne and M. S. Powell, "Benchmarking comminution energy consumption for the processing of copper and gold ores," *Minerals Engineering*, vol. 65, pp. 109–114, 2014.

[54] J. Tshisekedi, "Energy consumption standards and costs in the South African mining industry," M.Sc. thesis, Department of Engineering, University of Witwatersrand, 2007.

[55] E. Menon, *Piping Calculations Manual*. New York: McIntosh Engineering, 2005.

[56] R. L. . Kotze and J. K. Visser, "AN ANALYSIS OF MAINTENANCE PERFORMANCE SYSTEMS," *South African Journal of Industrial Engineering*, vol. 23, no. November, pp. 13–29, 2012.

[57] Y. Cengel and A. Ghajar, *Heat and Mass Transfer*, Fifth. New York: McGraw Hill Education, 2015.

[58] G. Shuttleworth, "Benchmarking of electricity networks: Practical problems with its use for regulation," *Utilities Policy*, vol. 13, no. 4, pp. 310–317, 2005.

[59] Accutrak, "Accutrak products," 2018. [Online]. Available: http://www.accutrak.co.za/our-products-2/smartrail/. [Accessed: 22-Jun-2018].

[60] P. Baloyi, "Software analyses rock transported underground," *Mining weekly*, pp. 4–7, April 2009.

[61] Y. Chambati and L. D. Meyer, "Investigate the effectiveness of the Smart Rail Measuring System at Tumela Mine 15 East Shaft," *Nova Journal of Engineering and Applied Sciences*, vol. 4, no. 2, pp. 1–10, 2015.

Appendix A: Operational efficiency management strategies

Supply side management

Oversupply of CA is avoided by characterisation of the CA network requirements and matching the supply with the required demand. Optimising the compressor control strategy is a crucial part of supply side energy management. The supply of CA is controlled with load sharing, compressor selection and guide vane control [14].

The air supply of individual compressors can be controlled by regulating the guide vane angles on the air intake of the compressor [11], [13], [19]. Lowering the discharge air flow rate of the compressor, puts less strain on the driving motor which results in less energy generation.

Different compressors vary in size and efficiency. Most CA networks will have different types and size compressors installed [11]. Energy savings can be achieved when the load from the CA demand is shared by the most efficient compressors [8], [11], [19]. Because the CA demand varies during the day, the compressors should be scheduled appropriately to avoid oversupply of CA.

The compressor schedule should therefore be optimised so that the supply matches the required demand with the most efficient compressors active. Supply side management is limited when the CA requirements cannot be characterised accurately.

Demand side management

Demand side initiatives are implemented to reduce the CA demand of the network. Less air needs to be supplied to the network to satisfy a reduced demand. Therefore, the compressors can be controlled optimally to supply less air and to lower the amount of electricity consumed [8], [14].

Control valves

The air demand can be regulated with control valves installed on surface and underground [10], [11]. Valve openings are varied to regulate the amount of air that passes through the valve and so doing, controls the downstream pressure of the CA network. Control valves are used to prevent oversupply of CA and to minimise wastage through leaks when the CA demand is low. Different types of valves are available depending on the application.

Butterfly - and globe valves are the most common type of valve used for CA in the mining industry [12]. High performance and standard butterfly valves are used where high performance butterfly valves provide better corrosion resistance than standard butterfly valves at a slightly increased cost [11]. Butterfly valves are mostly used for open/close type of control because of the excessive noise and vibrations emitted when these valves are used to reduce the airflow [11], [12]. Butterfly valves are also easily worn when used to reduce air flow and therefore offer poor reliability when used to control the downstream air pressure. Completely isolating parts of the CA network is not always possible, because some applications require a constant supply of CA throughout the day, such as refuge bays [11].

A downstream pressure setpoint should be maintained to supply adequate CA and therefore precise control is required. Globe valves are used when high quality control is preferred because the flow curve of a globe valve tends to be more linear and can even be customised by changing internal parts of the valve [10]–[12]. Globe valves are ideal for downstream pressure control without the negative effects of corrosion [12] but unfortunately, globe valves are extremely expensive. Globe valves are approximately five times more expensive than butterfly valves [11], [12] and the valves are not the only infrastructure required for a control loop. A typical butterfly- and globe valve is illustrated in Figure 24.
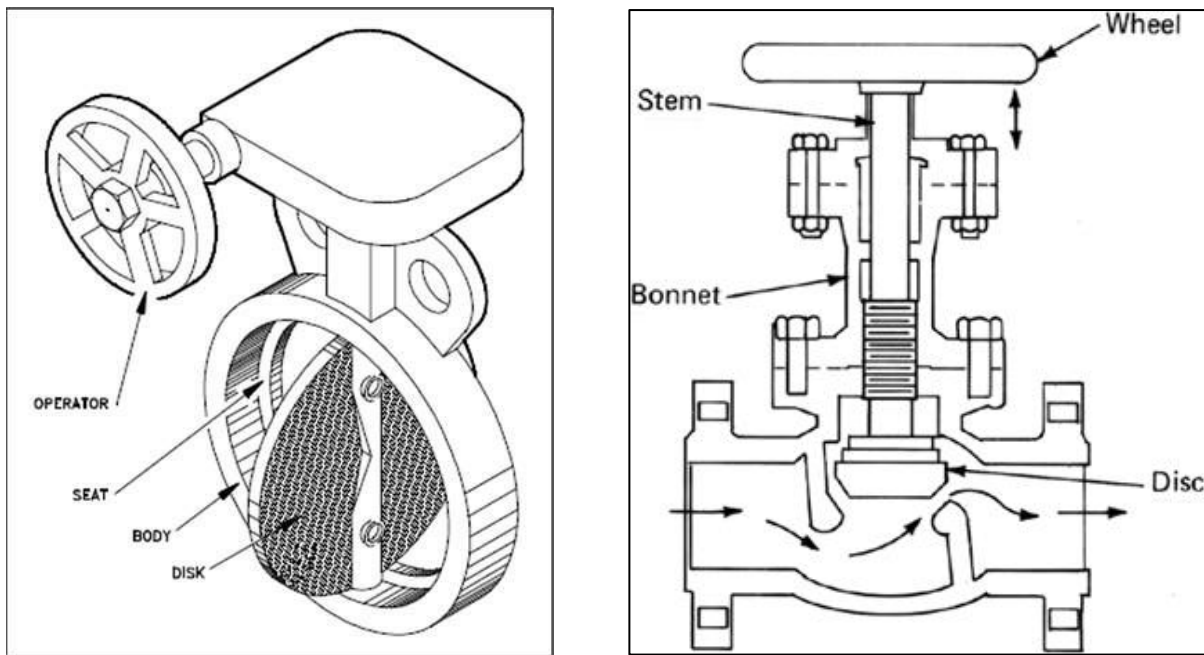
Figure 24: Butterfly valve (left) and globe valve (right)[6]

The control valve assembly usually consists of a valve, actuator, flow transmitter, pressure transmitter and programmable logic controller (PLC). Actuators are used to change the position of the valve by applying a force. Different types of actuators exist, but electric and pneumatic actuators are most commonly used in the mining industry [12]. A supervisory control and data acquisition (SCADA) system connected to a PLC is used to control electric or pneumatic actuators from a remote location [10]. The control system requires pressure – and flow transmitters to monitor the state of the CA and to determine valve positions.

The costs of control valves are highly dependent on the size of the pipe diameter and therefore, to lower the cost when quality control is required, an alternative valve configuration is usually installed [12]. The alternative configuration includes installing a butterfly valve in the main pipeline and a smaller globe valve on a bypass pipeline with a smaller diameter. The proposed configuration is illustrated in Figure 25.

---

[6] Valtorc, "Valves and actuators", Kennesaw, GA. [Online]. Available: http://www.valtorc.com/valve-news/difference-between-a-double-and-triple-offset-butterfly-valve [30 July 2018].
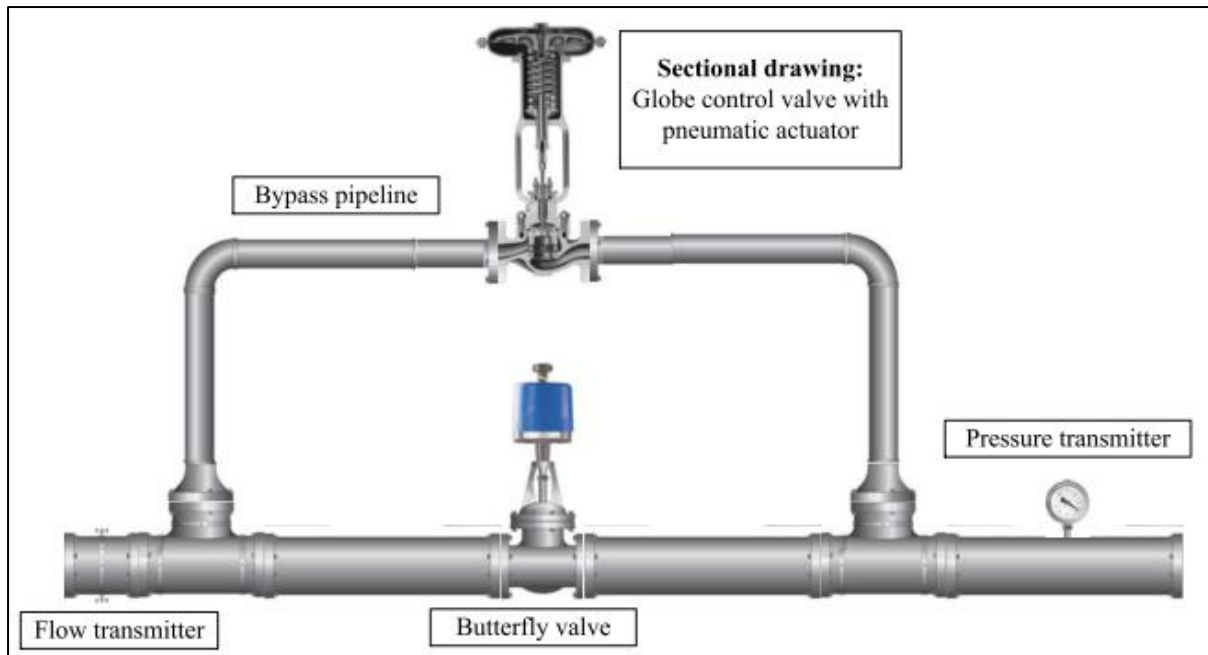
Figure 25: Bypass valve configuration [12]

The cost of infrastructure is reduced because of the smaller globe valve required while still providing adequate control of CA through the pipeline. The CA is controlled to obtain a desired downstream pressure by closing the butterfly valve on the main pipeline and varying the globe valve opening on the bypass pipeline. Other instrumentation essential for control is however still required for this configuration.

Control valves are installed in the compressed air network at strategic locations on surface and underground. Surface control valves are typically implemented on the main CA supply, leading to the shaft. The valve is set to a predetermined pressure setpoint to regulate the air flow entering the shaft. The downstream pressure of the entire shaft is therefore maintained with the surface control valve.

The required pressure of the system is determined by the highest pressure demand in the system [10]. Therefore surface control can be very limited if the underground demand is not synchronised [10].

Underground control valves are installed to better control the demand of different mine sections. The same configuration is required as the control valves installed on surface. Control valves are normally installed near the shaft on every level to regulate the airflow to various underground levels independently. By regulating the supply flow on various levels, different levels can have a different air pressure. By optimally

controlling the pressure of each level to match the required demand, more energy savings can be achieved than matching the highest demand of the entire mine with surface control valves. This option does however come at a higher price, because instrumentation is required on every level underground.

Control valves are very effective to reduce oversupply of compressed air, resulting in cost savings due to less energy generation from the compressors. However, control valves offer very little in wastage reduction due to leaks and other losses, especially at times when the CA demand is high.

Reducing wastage

Any wastage of CA can cause a significant increase in the CA demand. Compressors need to consume more energy to satisfy the increased demand which leads to higher generation costs [11].

Leaks are the most significant contributor to CA wastage in mines. Leaks can cause air pressure losses of up to 30% from the supply to the working areas [23], which adversely affects production rates [21]. In poorly maintained systems up to 50% of CA consumption can be wasted through leaks [21]. A leak in a CA system is defined as any opening where CA is released in to the atmosphere without authority or unintentionally.

The harsh environment underground and the complexity of the CA network, results in high probability of leaks. The main causes of underground leaks can be attributed to accidental damage, vandalism, improper use, poor maintenance and negligence to isolate air to inactive mine sections.

Stope isolation valves have been implemented on many occasions in an attempt to minimise leaks when no CA is required in the working places (outside of drilling shift). Stope isolation valves are valves that isolate CA to reduce air leakage and improper usage of CA in the working areas. Stope isolation valves are situated at the working places deep in the mine. The high costs and communication problems associated to instrumenting automatic valves deep in to a mine, means these valves must be manually operated. It was found that rock drill operators (RDOs) have no interest in

reducing wastage and therefore neglect to close isolation valves due to negligence [9]. In addition, some work areas have inadequate ventilation and therefore CA is used to ventilate head raisings to prevent toxic gasses from entering work areas even when workers have vacated.

It is clear that stope isolation valves are not used effectively to reduce wastage in the work areas and they have no effect on the losses due to leaks during the drilling shift. Additionally, wastage due to leaks can be present at any location in the underground network and therefore other means of reducing leaks is required.

Finding and fixing leaks is a challenging task that requires a lot of resources [11], [22]. Locating leaks is even more challenging in an underground CA network that can extend for several kilometres on every level. Currently the limited maintenance performed on the CA network is done by fixing the most substantial leaks that is detected by mine managers via manual audits.

Reducing friction losses

The age of the CA pipe network influences pressure losses that occur over pipe sections [7]. Higher losses result in the compressors working harder to supply more air to maintain a high pressure at the end users.

Pressure losses occur in pipe sections because of pipe friction and therefore longer sections will experience more pressure losses than sorter sections. Certain factors can contribute to the friction inside a pipeline. These factors include, bends, blockage, corrosion and varying diameters.

Different initiatives can be implemented to reduce the pressure losses experienced in a CA network. Losses experienced from inefficient pipe network configurations can unfortunately only be rectified by replacing/reconfiguring the pipe network or sections of the pipe network [7]. Examples of an inefficient configuration is one with multiple unnecessary tight bends, pipes with small diameters that extend to larger diameters and unnecessarily long pipe sections.

The moisture content in CA can cause corrosion in the inside of the pipeline to occur over a period of time. Corrosion effects the surface roughness of the pipeline which

increases the pressure losses over a pipe section [6], [7]. Unfortunately, it is difficult to detect where excessive corrosion has already occurred, but it can be prevented to some extend by installing efficient water traps [6].

Like wastage, pipe sections with substantial friction losses are challenging to locate in an extensive CA network. Currently management of wastage and losses is very limited in the mining industry when faced with extensive CA networks.

Appendix B: Article submitted, based on this study

An article is appended as edited by the journal of Sustainable Production and Consumption.

Research article

Local benchmarking in mines to locate inefficient compressed air usage

Daniel du Plooy [*], Philip Maré, Johan Marais, Marc J. Mathews

Centre for Research and Continued Engineering Development, North-West University, P.O. Box 11207, Silver Lakes, 0054, South Africa

A B S T R A C T

Compressed air is a vital source of energy for deep mines. It is therefore alarming that leaks, wastages, and losses are the highest contributing factors to the deterioration of compressed air network efficiency. However, locating these losses in the extensive underground compressed air networks are both challenging and time-consuming. This study therefore introduces a novel method to locate inefficient compressed air usage in an underground mine. Local benchmarking using the correlation between the compressed air supply and production was thus employed to identify inefficient usage.

The methodology was applied to the underground network of a platinum mine as a case study. The proposed local benchmarking methodology was able to identify levels with sizeable compressed air inefficiencies. Verification was then done by implementing wastage reduction initiatives on the entire underground network and comparing the results with the identified levels. It was thus verified that the methodology could be used to identify and prioritise local compressed air inefficiencies in an underground mine. Regression analysis was used to visualise and quantify the improved efficiency of the entire underground compressed air system. Implemented initiatives reduced compressed air consumption while an increase in productivity was observed, which highlights the importance of energy management in an underground mine. The proposed methodology provides a practical support tool that can be used by mine managers for underground compressed air networks. The methodology identifies the potential for compressed air wastage reduction and guides improvement efforts within individual mines.

© 2018 Published by Elsevier B.V. on behalf of Institution of Chemical Engineers.

1. Introduction

1.1. Background

Compressed air is considered one of the most expensive utilities on a mine (Kriel et al., 2014), compressors can contribute up to 21% of the total electricity demand of a typical mine (Cilliers, 2016a). However, compressors are still regarded as the norm to supply energy to underground equipment in South African mines, because of their ease of use, consistency and scalability. In addition to the high costs, the amount of compressed air flow required for production has increased by more than twofold in the past decade (Bester et al., 2013).

It was also found that leaks, wastages, and losses are the most significant compressed air consumers in an underground mine and can contribute up to 70% of the total underground compressed air demand (Bester et al., 2013; Cloete et al., 2013). Mines can have compressed air systems with total installed capacities of up to 85 MW (Kriel et al., 2014), with typical capacities ranging from 16 MW

to 22 MW (van der Zee, 2014; Bredenkamp et al., 2015; Heyns, 2014; Vermeulen et al., 2017). If 2018 Industrial electricity tariffs are used to calculate the cost then leaks, wastages and losses can contribute up to $ 6.43 million per annum in electrical costs.

Further, inefficient compressed air usage not only increases electricity costs but also lowers service delivery at the working areas. Furthermore, leaks and other wastages can cause a significant pressure drop which is directly correlated to the amount of ore produced (Bester et al., 2013; Cloete et al., 2013; van der Zee, 2014). Leaks and wastage of compressed air therefore not only increases generation costs but also lowers production rates.

Comprehensive studies have thus been conducted in order to determine the different energy saving initiatives that can be implemented to reduce compressed air wastage on mines (Bredenkamp et al., 2015; Heyns, 2014). Demand-side management of compressed air is typically used to reduce wastage and leaks present in the compressed air network by implementing various energy saving initiatives (Kriel et al., 2014; Vermeulen et al., 2017; Maré et al., 2017). However, underground compressed air networks can be large and complex, and savings initiatives are often constrained because of time, resources and the costs required to implement them (Bredenkamp et al., 2015). Areas, where energy efficiency

---

improvements can be achieved, must thus first be identified before initiatives can be implemented, especially on the demand-side (Bredenkamp et al., 2015; Heyns, 2014).

Literature covers many compressed air management techniques that can be used to identify inefficiencies. The relevant techniques and their applicability to an underground mine network are discussed in the following section.

1.2. Literature review

Leaks are considered to be the main contributors to inefficiencies in compressed air networks (Reddy et al., 2011a). Leaks in compressed air systems can cause consumption losses of up to 50% (Dindorf, 2012) and pressure drops of up to 30% in pipe sections supplying work areas (Da La Vergne, 2003). However, locating leaks in extensive underground networks is a challenging task.

Murvay et al. identified the state of the art leak detection methods and separated them into hardware and software-based methods (Murvay and Silea, 2012). A thorough review of these methods and their shortcomings found that none of them are practical for use in an underground mine. Hardware based methods require personnel to patrol the entire network. In complex networks that extend more than forty kilometres (Ital and Lu, 2007) patrolling pipelines on a regular basis in this manner is not practical.

Software-based methods require monitoring instrumentation to be installed at all sections of the pipeline. This is also not practical in an underground network. The reasons for this impracticality include high installation and maintenance cost (Ital and Lu, 2007), poor infrastructure for data transmission (Love et al., 2016) the harsh underground environment as well as the risk of theft and damages. Some of the traditional leak detection methods could be useful for detecting compressed air inefficiencies if the scope is narrowed to smaller sections of the mine (Dindorf, 2012; Reddy et al., 2011a; Murvay and Silea, 2012; Mekid et al., 2017; McAllister, 2014; Jin et al., 2014; Datta and Sarkar, 2016; Paffel, 2017; Reddy et al., 2011b; Luís et al., 2017; Brodetsky and Savic, 1993; Abdulshaheed et al., 2017; Soldevila et al., 2016; Cugueró-Escofet et al., 2015; Goulet et al., 2013). This is however unlikely due to the typical constraints faced in leak detection and does not offer a solution to the holistic detection of compressed air inefficiencies. Therefore a different technique, focusing on narrowing the scope of detection to smaller sections, should be explored.

Benchmarking has proven to be an effective method to determine the scope for energy saving initiatives and provides useful insight into energy and resource inefficiencies (Maré et al., 2017). Benchmarking is typically done within the context of assessing comparative energy efficiencies in order to evaluate performance compared to some reference performance (Cilliers, 2016a).

Benchmarking studies utilise different quantifiable key performance indicators (KPIs) for comparison among peers. By analysing and comparing benchmarked performance scores, valuable insight can be gained into the energy efficiency of different systems (Cilliers, 2016a). This same methodology should apply when identifying inefficiencies in compressed air usage since compressed air is one of the primary sources of energy underground (Cilliers, 2016a,b).

Various benchmarking studies have been implemented on mine compressed air systems (Cilliers, 2016a; van der Zee, 2014; Wang et al., 2016; Ballantyne and Powell, 2014; Tshisekedi, 2007). From these studies, variable factors like technology, infrastructure, environment, depth, and allocation of resources play a significant role in the accuracy of benchmarking. These previous studies evaluated the usage and production of an entire mine and then compared the findings to other mines with similar energy governing factors. Benchmarking the total aggregated usage for comparison

of different plants with similar energy governing factors in this manner is known as global benchmarking. Global benchmarking however requires complex grouping techniques (van der Zee, 2014), mathematical manipulation (Cilliers, 2016b), or reasonable assumptions (Tshisekedi, 2007) for accurate comparisons.

In contrast, Local benchmarking can be defined as an intra plant comparison of performance measures (ElMaraghy et al., 2017). In Local benchmarking, key performance indicators (KPI) are evaluated for different sections of the same plant in order to locate and quantify inefficiencies at a line level. A local benchmarking study was previously implemented at line level in order to evaluate the energy usage of computer numerical control (CNC) machines in an industrial plant (ElMaraghy et al., 2017). Multiple CNC machines were compared to gain insight into the energy use and wastage of the different machines. The study emphasised the need for benchmarking at line level to mitigate the challenges faced with comparing data from different plants.

A thorough review of literature found that no benchmarking methodologies have been implemented locally in the mining industry. A study done by Bunse et al. (2011) has revealed that benchmarking and KPIs are standard practice at an aggregated plant or sector levels, but benchmarking on line level is still relatively absent from literature. Benchmarking compressed air at line level could thus be used to determine efficiency and wastage of different mine sections if an appropriate comparison method is developed.

1.3. Need for study

Wastage and losses of compressed air in the mining industry need to be managed in order to ensure lower generation costs and better service delivery to improve production rates. Because of the extensive compressed air network in an underground mine, an energy management tool is required to locate wastage reduction opportunities. Research found that although many methods are prescribed to locate gas leaks in pipelines, none of these methods are practical for implementation in an underground mine. Additionally, compressed air inefficiency is not limited to leaks.

Global benchmarking has proven to be a successful method for determining the scope of energy inefficiencies in the mining industry, however no insight could be gained on where to achieve these improvements locally. Further, Local benchmarking has been implemented in the industrial sector to locate energy wastage, but a thorough review of energy benchmarking literature found no instances of local benchmarking in the mining sector. Lastly, no practical method currently exists to determine local compressed air inefficiencies in an underground mine.

The literature review indicated the need for a practical methodology in order to locate local inefficiencies of compressed air in an underground mine. Therefore the purpose of this study was to investigate if local benchmarking can be used to identify and improve compressed air inefficiencies in an underground mine network. The proposed methodology examines compressed air usage of multiple sections underground in order to determine unnecessary wastage in individual plants. The methodology also offers an energy management support tool that is absent from the previous literature.

2. Methods

2.1. Site-specific information

The underground compressed air network of a South African platinum mine was selected as a case study. Due to confidentiality, the name of the mine is not disclosed in this report. The scope of the study was limited to the central shaft and the underground network of the investigated mine.

Accurate data acquisition is an essential pre-requisite for benchmarking (Cilliers, 2016a; ElMaraghy et al., 2017). Underground layouts were thus obtained and investigated in order to get a better understanding of the underground compressed air network. Active work areas and development areas were identified as well as the compressed air instrumentation installed underground. Fig. 1 illustrates the underground compressed air network of the central shaft.

The compressed air network extends from the surface to underground via a 350 mm and a 600 mm diameter pipeline. The pipelines are connected on 22L to form what is referred to as a ring feed.

The underground network is not connected to the underground network of any other shaft and is therefore isolated. The top underground levels include 11L to 21L which are supplied with compressed air from the 600 mm pipeline. Each of the top levels has working instrumentation installed that includes a flow transmitter, pressure transmitter, and control valve.

The declines range from 22L to 25L. The decline levels comprise of a Merensky and an Upper Group 2 (UG2) Reef. Each of the levels going into the Merensky and UG2 Reefs are split again to a West and East side. The splits lead to the working areas where most of the compressed air is utilised by rock drills (Joubert, 2010). All the decline levels are supplied with compressed air via the 600 mm and 350 mm pipelines due to the ring feed on 22L.

2.2. Data acquisition methodology

In order to implement local benchmarking, appropriate energy-related KPIs need to be determined and compared for different sections of the mine (May et al., 2015). Previous compressed air benchmarking studies (Kriel et al., 2014; Cilliers, 2016a; McAllister, 2014; Jin et al., 2014) compared compressed air electricity consumption in order to estimate the scope of compressed air electricity savings that can be achieved on a specific site. However, for local benchmarking, comparing electricity consumption per section is not possible. Therefore, this study requires a different KPI for comparison.

The relationship of the parameters that influence energy consumption needs to be determined before an appropriate KPI can be selected (May et al., 2015). Literature found that air pressure at the working areas is linearly proportional to the amount of ore produced (Bester et al., 2013; Cloete et al., 2013). Compressed air inefficiencies are however responsible for pressure losses and consequently there should be a direct correlation between compressed air inefficiencies and production rates (Cilliers, 2016a; van der Zee, 2014).

Recent studies evaluated typical KPIs used for compressed air benchmarking in the industrial sector (Salvatori et al., 2018; Bonfà et al., 2017). The studies found that the ratio between the volume of compressed air and the production volume can be used to evaluate the distribution performance of the compressed air. This KPI can also be used to evaluate the waste, losses, and improper use of compressed air. Therefore, compressed air consumption based on production was selected as the appropriate KPI for comparison per section.

The selected KPI requires compressed air flow rate and production rate data to be collected at each section of the mine. Permanently installed flow meters are typically used to determine usage per unit time (ElMaraghy et al., 2017). Therefore, previously installed Rosemount Annubar flow meters were used to obtain the compressed air usage of different sections underground. Data was also collected to calculate daily averages over a period of a month to filter out anomalies that may occur in day to day operation.

There is no instrumentation installed on the declines that can determine compressed air flow usage and therefore a manual data audit was required in order to obtain data for benchmarking. Portable flow meters were installed for a week to obtain the required data. A VA 500 insertion mass flow meter from CS Instruments was used to log the average flow rate at an interval of two minutes.

These flow meters required a valve fitting to insert the flow meter into the compressed air pipeline. Limited measuring points were thus found in the main haulages of the declines, and therefore manual measurements were conducted in the West and East split of each decline level. The location where manual measurements were taken are illustrated with a red circle in Fig. 1.

Due to time constraints and equipment challenges, longer periods of data could not be logged. However, the measuring period should be large enough to evaluate the daily consumption characteristics and filter out anomalies.

The databases containing the logged data of energy meters were often found to be inaccurate or incomplete (Kriel et al., 2014; Brodetsky and Savic, 1993; Abdulshaheed et al., 2017). Therefore, it is crucial to evaluate the integrity of the obtained data before any analysis can be done. The integrity of the obtained period of data was evaluated by looking for any discrepancies and abnormally high or low values present. No data loss or any other abnormalities were found in the logged database during the period of evaluation.

2.3. Benchmarking methodology

Preliminary benchmarking was done after sufficient data was collected. It was determined from the obtained layouts and available data which sections were the most practical to compare since if smaller sections are compared, wastage can be allocated to smaller sections. For this study, the average flow consumption and average production rate of each level were compared so that accurate comparison could be made between top levels and sections on the declines.

Typical benchmarking studies include formulating KPIs to obtain the ratio of consumption and production rate in order to demonstrate an efficiency correlation. Some sections of the mine however require more air than other sections due to an uneven capacity of working areas and pneumatic equipment.

The efficiency improvement per level will also not necessarily translate linearly to overall system efficiency improvement. For example, if the efficiency of a specific level is low, but the air consumption is also low, then improving the efficiency of the level will not improve the overall system efficiency by the same magnitude. It will therefore not be very beneficial to investigate levels with low compressed air consumption, even if the ratio of air consumption to production is poor.

In Section 2.2 it was found that the ratio of compressed air usage to the amount of output production is an applicable KPI to use to evaluate and locate inefficiencies present in the network. KPIs were thus normalised to prioritise areas where local efficiency improvements would lead to total system efficiency improvements. The following equation was developed to normalise the data and get a better indication of how levels should be prioritised.

$$\text{Section}_{indicator} = KPI \times \left(\frac{C_{factor} + P_{factor}}{2} \right) \qquad (1)$$

In Eq. (1) the KPI is the total compressed air consumption for each section in m^3/h divided by the total ore produced in each section measured in tonnes. The KPI per section was thus normalised by multiplication of the consumption (C_{factor}) and production (P_{factor}) factors. The C_{factor} is the compressed air consumption per section divided by the total consumption per shaft in m^3/h. The P_{factor} is the tonnes produced per section divided by the total shaft production.

The section indicator ensured that benchmarking was done in such a manner as to identify efficiency improvement opportunities
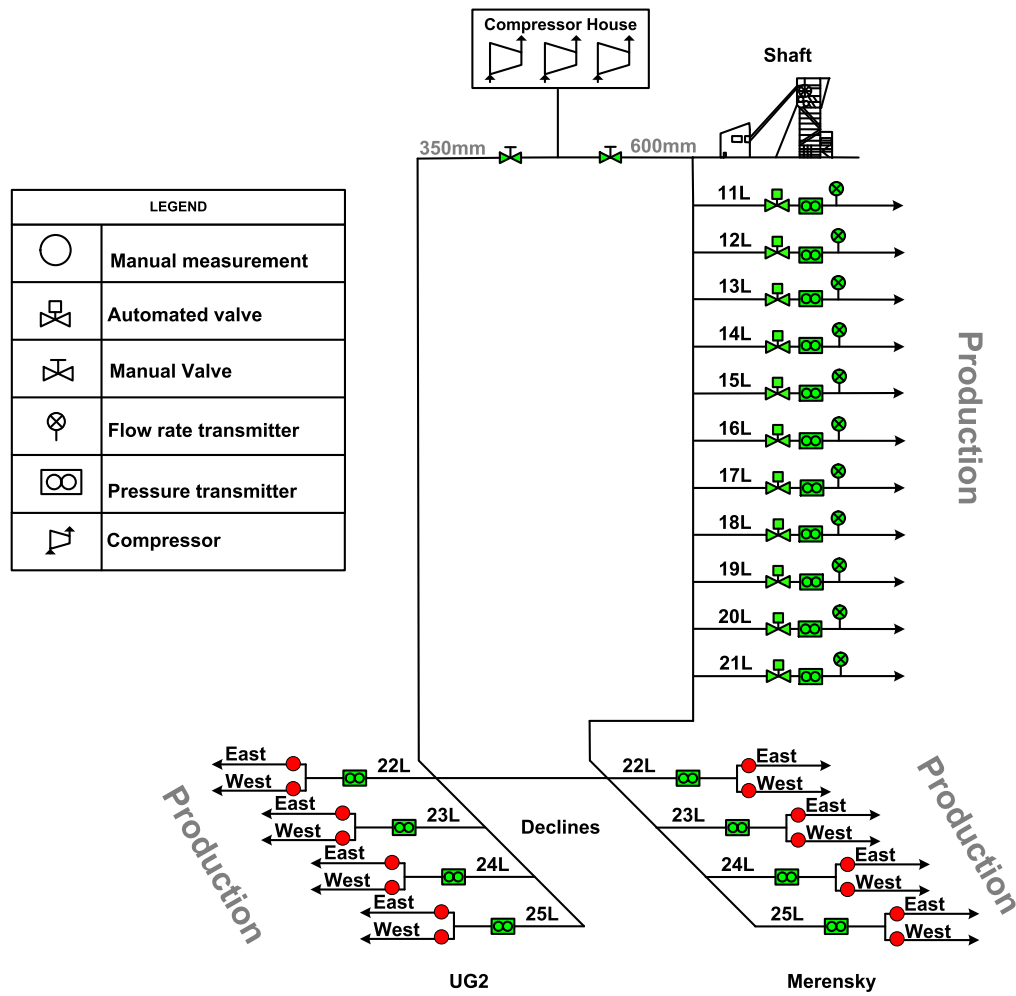
Fig. 1. Central shaft underground layout. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

appropriately by taking in to account the magnitude of air usage and not just the efficiency of air usage per section. The higher the indicator value, the more scope was thus identified for overall system improvement.

It should be noted that normalisation and grouping techniques used in previous global benchmarking studies (Cilliers, 2016a; Mekid et al., 2017; McAllister, 2014; Jin et al., 2014) were not necessary because variable energy governing factors stay relatively constant if benchmarking is done on different sections of the same mine. For example, ambient temperature and technology will not vary a considerate amount from one section to the next.

2.4. Verification methodology

Levels were prioritised from the normalised benchmarking results based on which levels would provide the most opportunity to improve the efficiency of the total compressed air network. To verify if the levels were prioritised correctly, a detailed compressed air audit was conducted on the entire underground compressed air network. A detailed audit is presently the most effective and accurate method of determining compressed air network inefficiencies in deep-level mines (Koski, 2002). The entire network was evaluated through visual inspection and manual measurement of pressure and flow rate using a VA 500 insertion flow meter and a KIMO pressure logger. The audit was done in the context of identifying inefficient compressed air usage in order to implement

corrective measures which would result in improved compressed air usage per level.

Following the compressed air audit, wastage reduction initiatives were implemented on the entire compressed air network, and the results of each level were compared to the prioritised levels. However, merely comparing the results of the change in air consumption is not sufficient because production rate is not constant and from literature it was found that production rate is the primary driver of the amount of compressed air used (Dindorf, 2012).

The change in consumption of each level was thus compared to the mines total consumption that was initially measured. This was done in order to ensure that the improvements made per level translated significantly to overall system improvements. This also ensures that results stay comparable if production rates have changed. The results were thus multiplied with the change in production rates. This could be done since production is the primary driver of compressed air consumption and literature suggest that the relationship between the production and consumption is linear. Eq. (2) was thus developed in order to compare efficiency improvements made by each section appropriately.

$$N = \frac{Q_1 - Q_2}{Q_T} \times \left(1 + \frac{P_2 - P_1}{P_1}\right) \tag{2}$$

Eq. (2) illustrates the normalised improvement impact as a percentage (N). The compressed air consumption in m^3/h before (Q_1) and after improvements (Q_2) are subtracted to indicate the amount
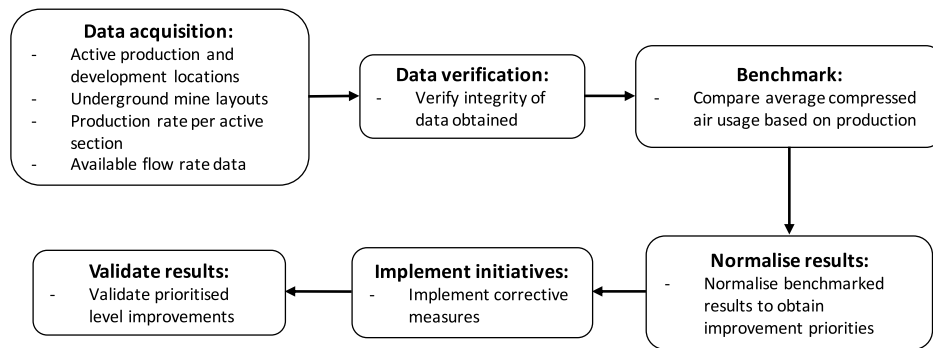
Fig. 2. Local benchmarking methodology.

of improvement per level. This Improvement is then divided by the total shaft consumption that was measured during the initial audit (Q_T). The change in production is denoted by the second factor which is the difference in production rate in tons per day after improvements (P_2) and the initial production rate (P_1), divided by the initial production rate.

Different improvement initiatives exist for compressed air (Cloete et al., 2013; Heyns, 2014; Cigueró-Escofet et al., 2015). These initiatives include supply and demand side optimisation. Optimising the supply side involves controlling the supply of compressed air to match the required demand. Oversupply can therefore be combated with the characterisation of required demand and by implementing demand-side initiatives. Demand-side initiatives include but are not limited to flow rate control through control valves, isolating inactive sections, fixing leaks and reconfiguring pipelines.

If the demand side has been optimised to reduce wastage, the supply of compressed air can be lowered to match the lowered demand. Further, only once the supply of compressed air is lowered, can wastage reduction result in cost savings. For this study, demand side initiatives were therefore implemented to reduce wastage and improve overall compressed air efficiency.

In summary, in order to verify if the proposed methodology can be used to identify and improve inefficiencies in an underground mine network, it was verified that implemented initiatives identified through an audit correlate to the levels prioritised as per the new methodology.

2.5. Validation methodology

For the methodology to be valid, the local efficiency improvements made should translate to total system efficiency improvements. Regression models of consumption and production were thus compared before and after initiatives were implemented. Efficiency is a measurable value that is determined by the ratio of outputs to inputs. Therefore, the efficiency improvement of the compressed air system would be validated if a definite improvement in the output to input ratio could be seen. Improvements can be quantified with the gradient of a best-fit line of input and output data points.

For the system efficiency improvement to be valid, there needs to be a clear correlation between input and output of the system after improvements were made. The correlation between input and output of the system can be quantified by the system effectiveness. Literature suggests a linear relationship between compressed air consumption and production rate (Cilliers, 2016a; van der Zee, 2014). The relationship between data points and a linear best-fit line can be quantified by the coefficient of determination (R^2) (Shuttleworth, 2005). In a previous benchmarking study, R^2 values higher than 0.6 was considered to be an indication of the proper relation between considered variables and the selected

best fit-line (Cilliers, 2016a). Therefore, for this study, an R^2 value higher than 0.6 after improvements served as validation of system effectiveness. Thereafter a significant improvement in the gradient of the selected best-fit line served as validation of improvement in total underground compressed air network efficiency.

In summary, in order to validate if the proposed methodology is suitable to identify and improve inefficiencies in an underground mine network, the overall system efficiency improvement was determined after initiative implementation. Fig. 2 illustrates an overview of the newly developed methodology.

3. Results and discussion

3.1. Benchmarking results

Preliminary benchmarking results were obtained by following the methodology described in the previous section. The preliminary benchmarking of the underground sections is illustrated in Fig. 3. The results contain the average compressed air flow usage in m^3/h and average production rates in tonnes of each level underground.

The ratio of compressed air usage vs production is visually illustrated for each level underground. The average daily compressed air usage is illustrated with a red bar, and the average daily production is illustrated with a thicker blue bar. If the ratio of compressed air usage to production is high (significant difference between red and blue bars), it is an indication that compressed air is not being used for production or other known operations and that compressed air is therefore being wasted.

From the preliminary benchmarking results, it was observed that the decline sections (22L to 25L) perform well when compared to the upper levels (11L to 21L) regarding usage vs production ratios. It is also known that the declines are relatively new compared to the upper levels. Therefore, the compressed air network in the declines was not corroded and abused by underground conditions to a similar extent as the compressed air network in the upper levels. The condition of the pipes might thus be a contributing factor to the efficient use of compressed air in the declines. Additionally, the decline levels are shorter than the top levels, and they therefore suffer fewer line losses. It was also seen that compressed air was supplied to sections that do not produce any ore (15L, 16L and 18L to 20L). These levels used compressed air for pneumatic loaders and rock drills that were utilised in non-production development that was taking place.

As stated previously, the preliminary benchmarked results provide insight into the compressed air efficiency of each level but do not explicitly illustrate the possible scope for overall system efficiency improvements. The results were therefore normalised in order to determine which level improvements would translate the most significantly to overall system improvements.
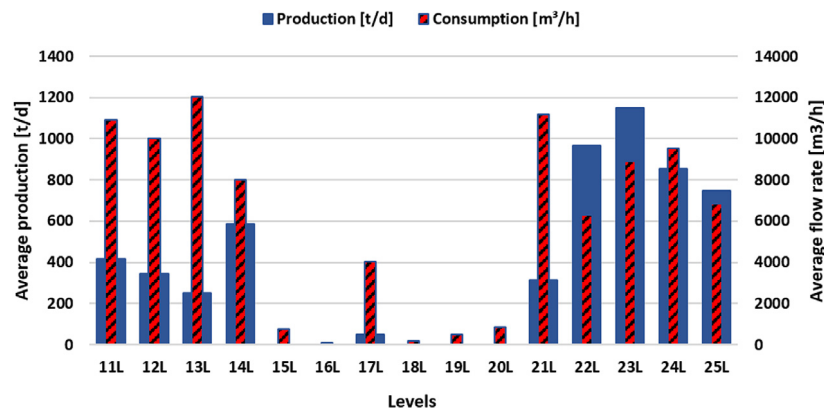
Fig. 3. Preliminary local benchmarking results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Normalised results

The normalisation method described in Section 2 was used to determine level indicators. The normalised results are illustrated with a Sankey chart in Fig. 4. The Sankey chart indicates the distribution of normalised results among different mining levels. The top level has the most significant distribution and is, therefore, the level that has the most potential for improvement. The normalised results indicate that 13L, 21L, and 11L have the most scope for overall efficiency improvement based on the ratio of compressed air usage versus production rate of the level as well as the amount of production and air usage compared to other levels.

It was already evident from the preliminary benchmarking results (Fig. 3) that 13L, 21L and 11L were among the levels with the most scope for improvement. However, it was not clear what the priorities of the levels should be in terms of overall efficiency improvements. Also, it required technical analysis and knowledge to determine which levels were a priority. The normalised results thus serve as a simple guide for mine managers that do not necessarily have the technical skills or knowledge to determine which levels should be prioritised. It also serves towards the eventual automation of the benchmarking methodology.

It should be noted that the normalised results exclude levels with no production. It was seen from the preliminary benchmarked results that these levels did not use a considerable amount of compressed air, compared to other levels. Upon further investigation, it was also found that they required the compressed air for development that was taking place. Normalising the levels with no production is also pointless since no reasonable comparisons can be made between consumption for production and consumption for development.

3.3. Verification of methodology

A comprehensive compressed air audit is required in order to determine the appropriate initiative to implement. The normalised results (Fig. 4) allow for these audits to be narrowed down to the most critical areas of concern. For this study, as a verification of the normalised results, a comprehensive full-shaft audit of the entire underground compressed air network was done. The audit took three months to complete with four personnel and was done in order to determine any source of inefficient compressed air usage. Minor leaks were found in almost all the working areas however, these leaks were small and were assumed to be a small contributing factor to the inefficient usage.

A good correlation between the improvements made and the top prioritised levels from benchmarking is required in order to verify the methodology. Monthly average flow rate and production data were thus used to determine the KPIs before and after

improvements were made. A summary of the audit findings and results are presented in Table 1.

The audit found that the primary cause of wastage was compressed air supply that was not cut off to sections that had been made inactive. Inactive sections are sections of a level that do not have any production, development or any other active operations that require compressed air. Manual measurements on 13L (highest priority level) indicated that approximately half (8000 m³/h) of the total compressed air that was being utilised by the level was supplied to an inactive section of the mine. The air supply to all other inactive sections was thus cut off in order to reduce the total compressed air wastage.

Some leaks and poor control was also identified as further causes of inefficient compressed air usage. It was found that 14L was not controlling the supply to match the required demand via the installed control valve on 14L. The problem was rectified by informing appropriate management personnel. Unfortunately, there were no control valves installed on the decline levels (22L to 25L), and therefore the primary cause of inefficient usage on the declines could not be rectified. No other concerns were found on the decline levels except for small leaks in the working areas. The audit findings in the decline levels thus correlated well with the results obtained from preliminary benchmarking.

Levels were given priorities ranging from 1 to 10 based on the normalised benchmarking results, which indicated that some levels had more scope to achieve overall compressed air efficiency improvements. The KPI improvements illustrate the improved efficiency of compressed air usage per level by taking into account the consumption and production rates per level. A strong correlation thus exists between the top three prioritised levels and the KPI improvement results. However, the KPI change only indicates the efficiency change per level. Therefore, the normalised improvement impact indicator (Eq. (2)) serves as a more appropriate verification indicator. This indicator takes in to account the change of compressed air consumption relative to the total shaft consumption and the relevant sections change in production rates.

The normalised improvement impact results correlate well to the top prioritised levels. It also indicates minimal changes in the decline levels where no initiatives where implemented. In addition, 80% of the total compressed air flow reduction achieved was due to implemented initiatives at the top three prioritised levels which means that 80% of the total consumption reduction could have been achieved by doing an audit at the top three prioritised levels only.

The changes of the KPI in the decline levels can be explained by the dynamic state of a mine. Mine pathways, development areas, and stoping areas change at a fast pace which influences the compressed air efficiency per level. The normalised improvement
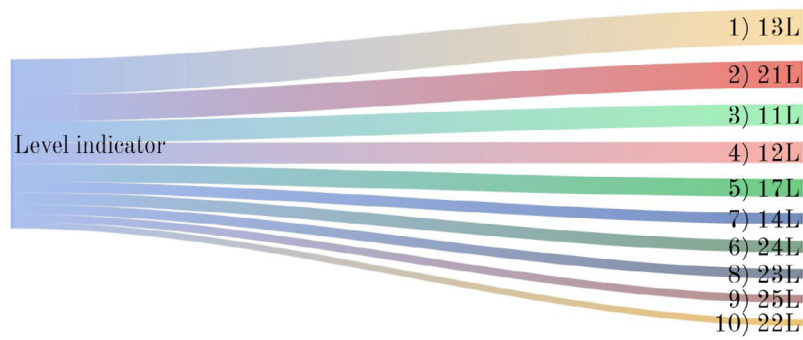
Fig. 4. Level indicator distribution.

Table 1
Summary of audit findings and actions.

Level	Findings	Action	Priority	KPI improvement	Normalised Improvement Impact - N
11L	Leaks in the main haulage / Supply to inactive section	Cut off supply to the inactive section	3	37.51%	2.51%
12L	Supply to inactive section / Leaks in working places	Cut off supply to the inactive section	4	-1.81%	1.35%
13L	Supply to inactive sections / Development taking place	Cut off supply to the inactive sections	1	60.95%	8.20%
14L	No control of supply	Implement valve control	7	22.76%	1.45%
17L	Development taking place	No action	5	-41.41%	0.38%
21L	Supply to inactive section / No control valves installed	Cut off supply to inactive section	2	58.14%	7.41%
22L	No control valves installed	No action	10	-33.92%	-0.11%
23L	No control valves installed	No action	8	1.66%	0.04%
24L	No control valves installed	No action	6	15.07%	-0.33%
25L	No control valves installed	No action	9	20.90%	-0.49%

impact indicator however shows that these changes only slightly impacted the overall efficiency of the mine (small changes where no actions were taken). The effect that these factors had on the system is visualised in the regression analysis in Section 3.4.

It should be noted that the improvement initiatives were implemented at all levels with no regard to the priorities that were determined. Therefore, the strong correlation that exists between the efficiency improvement results and the determined priorities serves as verification that the methodology can be used to prioritise levels appropriately.

3.4. Validation of results

It was verified that higher prioritised levels had the most scope to improve compressed air performance based on consumption and production rates. This was confirmed by the normalised improvement impact indicator (Eq. (2)). Verification was done under the assumption that the indicator illustrates the overall efficiency improvements of the system. This section thus validates the use of the developed indicator.

The implemented initiatives resulted in an average decrease of 30 022.06 m^3/h in total shaft consumption per day while an increase in productivity was observed. This is an indication that the system efficiency was improved. Regression analysis was thus done in order to visualise and quantify the system efficiency improvements made. A close relation between production rate and compressed air usage is expected for an effective compressed air system.

For a system with absolutely no wastage, a perfect linear relationship should be observed between the input and output of the system (Cilliers, 2016a). Regression analyses of the average
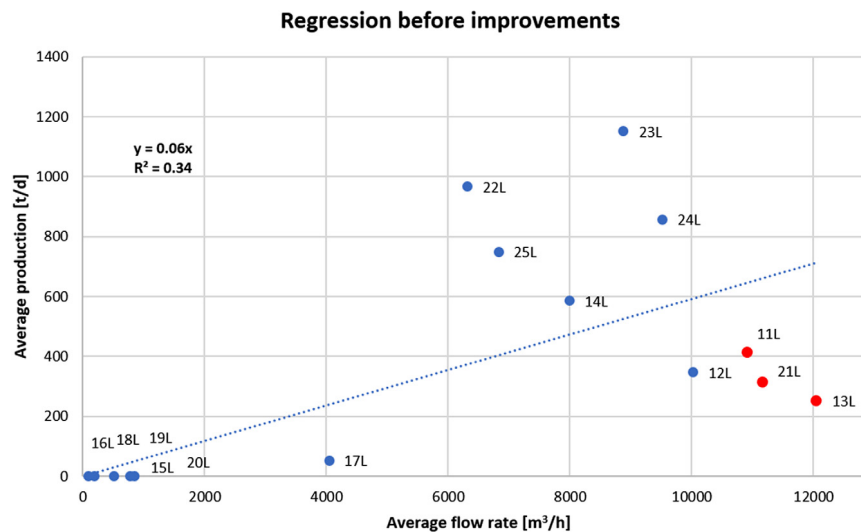
Regression before improvements

Fig. 5. Regression analysis before improvements.
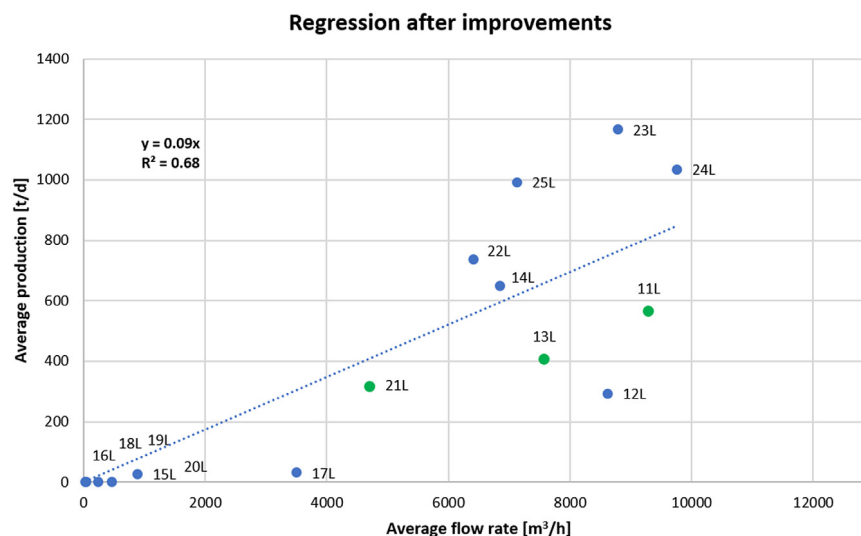
Regression after improvements

Fig. 6. Regression analysis after improvements.

production vs average consumption before and after inefficiencies were reduced, illustrate the improved efficiency of the compressed air system. The regression analyses are illustrated in Figs. 5 and 6.

The performance of the top three prioritised levels that were identified by the local benchmarking results are illustrated in different colours on the regression analysis. Levels with data points that are close to the bottom right of the regression figures are considered inefficient users, and data points that are close to the top left of the regression figures are considered efficient users.

Significant efficiency improvements can therefore be seen on the identified levels after improvements were made. A linear best-fit line was also inserted in order to illustrate the relationship of the input and output of the compressed air system. The R^2 value is an indication of how close the data are to the fitted linear regression line. After improvements were made, the R^2 value was 0.68, which is higher than the required 0.6 for validation of the linear best-fit line (Cilliers, 2016a). It is expected that the R^2 value will be lower than 1 since all the inefficiencies present in the compressed air system could not be rectified. Due to the large and complex network, and the nature of compressed air losses, it is thus not realistic to expect an efficiency of 100%. It is therefore not possible to obtain a perfect regression which in turn contributes

to the difficulties of determining the true relationship between production and consumption rates.

However, for this study there was a clear increase in system effectiveness after the compressed air inefficiencies were rectified. This, validates that local benchmarking can be a suitable means of determining compressed air inefficiencies in complex compressed air networks.

Furthermore, the efficiency of the system can be quantified by the improvement of the best-fit line gradient from 0.06 to 0.09. The gradient improvement indicates a better output to input relationship of the overall compressed air system. Therefore, the improved efficiency of the overall system validates that the efficiency improvements made per section effectively translated to overall system efficiency improvements.

3.5. Discussion of results

Literature showed that there is a need to investigate if local benchmarking can be used to identify inefficient compressed air usage in an underground mine compressed air network. This study found that it is possible to identify localised inefficiencies in mine

compressed air networks using a benchmarking method combining compressed air consumption and production. Rectification of these local inefficiencies further resulted in measured improvements in the overall compressed air system efficiency.

The value of the methodology described in this study is evident when one considers that the full compressed air audit conducted in the case study took more than three months to complete. An audit of this magnitude is not always practical and therefore identifying the levels that are wasting compressed air can serve as a useful energy management tool. Even though initiatives were implemented on the entire underground mine, 80% of the total reduced flow usage was due to implemented initiatives at the top three identified levels. Therefore 80% of the efficiency improvement could have been achieved by investigating only the top three identified levels. Therefore, local benchmarking of compressed air in an underground mine can be used as a powerful energy management tool.

A shortcoming of the methodology is however the requirement of a proportional relationship between compressed air usage and production. This limits the primary benefit of the methodology to active mining sections. The methodology would thus not accurately identify wastages and inefficiencies in development sections where limited, or no production occurs. However, necessary controls could be developed for such cases by looking at the normalisation techniques used by previous studies (Cilliers, 2016a; van der Zee, 2014; Wang et al., 2016; Tshisekedi, 2007).

A further limitation of the study is the validation using a case study that is not interconnected with other mines and compressed air networks as is typical in the platinum industry in South Africa (Kriel et al., 2014). The addition of a compressed air ring or further demands of interconnected mines may not yield the same results. Therefore, a further study should determine whether it is possible to use local benchmarking of more complex compressed air networks such as compressor rings with multiple mines or interconnected mines.

Utilising this methodology requires production data or any other form of output that is directly proportional to a measured input. Without the required data benchmarking will not be possible and manual audits will be required to locate inefficient compressed air usage. Furthermore, similar strategies could be applied to various other complex compressed air networks where there is a correlation between compressed air consumption and an output.

The efficiency improvements made by the installed initiatives resulted in a reduction of total shaft compressed air consumption while a slight increase in production was observed. The efficiency improvements also impacted the energy consumption of the supplying compressors. The average daily compressor energy consumption was reduced from 17 467 kW to 16 705 kW, which is approximately

$0.38 million per annum in cost savings. The results of the improved network efficiency, thus highlights the importance of energy management in an underground mine.

4. Conclusion

Previously no practical methods existed to identify localised compressed air inefficiencies on underground compressed air networks without spending an enormous amount of time and resources. This study therefore provides a practical method to locate compressed air inefficiencies more efficiently in an underground mine.

A methodology was thus developed to use local benchmarking to identify inefficient compressed air usage in an underground mine compressed air network. The benchmarking was done locally by comparing different sections of the same mine. Local benchmarking meant that the complicated techniques required

for global benchmarking were not required. A novel KPI was also used to compare different sections since typical KPIs used in previous studies were not applicable on a localised level. A platinum mine was then used as a real case study, and each level of the underground network was benchmarked and normalised in order to prioritise the levels that held the most significant opportunities to reduce compressed air inefficient usage.

A full and comprehensive audit of the underground compressed air network was conducted in order to validate if the prioritised levels hold the most significant improvement opportunities. The comprehensive audit identified cost saving opportunities of $ 0.38 million per annum. It was found that 80% of this total compressed air wastage could be allocated to the top three prioritised levels. Local benchmarking of compressed air in an underground mine can, therefore, be used as a powerful efficiency management tool.

The newly developed methodology can have a significant effect on the way underground compressed air networks are maintained. This tool can be used by mine managers to manage the allocation of resources and maintenance better. Greatly reduced audit times will serve as a motivation for mine managers to audit underground sections more frequently. Frequent audits will in turn result in improved service delivery and electricity cost savings of the compressed air system.

References

Abdulshaheed, A., Mustapha, F., Ghavamian, A., 2017. A pressure-based method for monitoring leaks in a pipe distribution system: A Review. Renew. Sustain. Energy Rev. 69 (2016), 902–911.

Ballantyne, G.R., Powell, M.S., 2014. Benchmarking comminution energy consumption for the processing of copper and gold ores. Miner. Eng. 65, 109–114.

Bester, S.J., Le Roux, D., Adams, D., 2013. The effect of compressed air pressure on mining production and energy demand. In: 2013 Proceedings of the 10th Conference on the Industrial and Commercial Use of Energy, ICUE.

Bonfà, F., Salvatori, S., Benedetti, M., Introna, V., Ubertini, S., 2017. Monitoring compressed air systems energy performance in industrial production: Lesson learned from an explorative study in large and energy-intensive industrial firms. Energy Proc. 143, 396–403.

Bredenkamp, J.I.G., Schutte, A.J., Van Rensburg, J.F., 2015. Challenges faced during implementation of a compressed air energy savings project on a gold mine. In: 2015 Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE, pp. 23–29.

Brodetsky, I., Savic, M., 1993. Leak monitoring system for gas pipelines. In: IEEE International Conference on Acoustics Speech and Signal Processing, vol. 3, pp. 17–20.

Bunse, K., Vodicka, M., Schönsleben, P., Brülhart, M., Ernst, F.O., 2011. Integrating energy efficiency performance in production management - Gap analysis between industrial needs and scientific literature. J. Cleaner Prod. 19 (6–7), 667–679.

Cilliers, C., 2016a. Benchmarking Electricity Use of Deep-Level Mines (Ph.D. thesis), School of Mechanical Engineering, North-West University Potchefstroom.

Cilliers, C., 2016b. Benchmarking electricity use of deep-level mine compressors. In: 2016 Proceedings of the 9th Conference on the Industrial and Commercial Use of Energy, ICUE, pp. 1–6.

Cloete, S., le Roux, D., Buhrmann, T., 2013. Reducing Compressed Air Wastage By Installing New Technology in Underground Mines. In: 2013 Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE.

Cugueró-Escofet, P., Blesa, J., Pérez, R., Cugueró-Escofet, M., Sanz, G., 2015. Assessment of a leak localization algorithm in water networks under demand uncertainty. IFAC-PapersOnLine 28 (21), 226–231.

Da La Vergne, J.N., 2003. Hard Rock Miner's Handbook, third ed. McIntosh Engineering, Ontario.

Datta, S., Sarkar, S., 2016. A review on different pipeline fault detection methods. J. Loss Prev. Process Ind. 41, 97–106.

Dindorf, R., 2012. Estimating potential energy savings in compressed air systems. Procedia Eng. 39, 204–211.

ElMaraghy, H.A., Youssef, A.M.A., Marzouk, A.M., ElMaraghy, W.H., 2017. Energy use analysis and local benchmarking of manufacturing lines. J. Cleaner Prod. 163, 36–48.

Goulet, J.A., Coutu, S., Smith, I.F.C., 2013. Model falsification diagnosis and sensor placement for leak detection in pressurized pipe networks. Adv. Eng. Inf. 27 (2), 261–269.

Heyns, G.P., 2014. Challenges Faced During Implementation of a Compressed Air Energy Savings Project on a Gold Mine (Ph.D. thesis), Department of Mechanical Engineering, North-West University Potchefstroom.

Ital, I.G., Lu, S.O., 2007. Addressing plant obsolescence with digital instrumentation and control systems. Power Eng. 120 (7), 32–35.

Jin, H., Zhang, L., Liang, W., Ding, Q., 2014. Integrated leakage detection and localization model for gas pipelines based on the acoustic wave method. J. Loss Prev. Process Ind. 27 (1), 74–88.

Joubert, R., 2010. Cost and Time Effective DSM on Mine Compressed Air Systems (M.Eng. dissertation), Departement of Mechanical Engineering, North-West University Potchefstroom.

Koski, M., 2002. Compressed air energy audit 'The Real Story'. Energy 99 (3), 59–70.

Kriel, C.J.R., Marais, J.H., Kleingeld, M., 2014. Modernising underground compressed air DSM projects to reduce operating costs. In: 2014 Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE.

Love, P.E.D., Zhou, J., Matthews, J., 2016. Systems information modeling: From file exchanges to model sharing for electrical instrumentation and control systems. Autom. Constr. 67, 48–59.

Luís, W., Silva, V., Carvalho, L., Souza, O., De Paula, M.R., 2017. Mechanic and energy. REM - Int. Eng. J. 70 (4), 421–428.

Maré, P., Bredenkamp, J.I.G., Marais, J.H., 2017. Evaluating compressed air operational improvements on a deep - level mine through simulations. In: 2017 Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE.

May, G., Barletta, I., Stahl, B., Taisch, M., 2015. Energy management in production: A novel method to develop key performance indicators for improving energy efficiency. Appl. Energy 149, 46–61.

McAllister, E.W., 2014. Pipeline rules of thumb handbook: A manual of quick, accurate solutions to everyday pipeline engineering problems. In: Pipeline Rules of Thumb Handbook, sixth ed. Elsevier Science & Technology, Boston, pp. 606–614.

Mekid, S., Wu, D., Hussain, R., Youcef-Toumi, K., 2017. Channel modeling and testing of wireless transmission for underground in-pipe leak and material loss detection. Int. J. Distrib. Sens. Netw. 13 (11).

Murvay, P.S., Silea, I., 2012. A survey on gas leak detection and localization techniques. J. Loss Prev. Process Ind. 25 (6), 966–973.

Paffel, K., 2017. Air-system leak. Hydraul. Pneumat. 70 (11), 22–27.

Reddy, H.P., Narasimhan, S., Bhallamudi, S.M., Bairagi, S., 2011a. Leak detection in gas pipeline networks using an efficient state estimator. Part-I: Theory and simulations. Comput. Chem. Eng. 35 (4), 651–661.

Reddy, H.P., Narasimhan, S., Bhallamudi, S.M., Bairagi, S., 2011b. Leak detection in gas pipeline networks using an efficient state estimator. Part II. Experimental and field evaluation. Comput. Chem. Eng. 35 (4), 662–670.

Salvatori, S., Benedetti, M., Bonfà, F., Introna, V., Ubertini, S., 2018. Inter-sectorial benchmarking of compressed air generation energy performance: Methodology based on real data gathering in large and energy-intensive industrial firms. Appl. Energy 217, 266–280.

Shuttleworth, G., 2005. Benchmarking of electricity networks: Practical problems with its use for regulation. Util. Policy 13 (4), 310–317.

Soldevila, A., Blesa, J., Tornil-Sin, S., Duviella, E., Fernandez-Canti, R.M., Puig, V., 2016. Leak localization in water distribution networks using a mixed model-based/data-driven approach. Control Eng. Pract. 55, 162–173.

Tshisekedi, J., 2007. Energy Consumption Standards and Costs in the South African Mining Industry. University of Witwatersrand.

van der Zee, L.F., 2014. Modelling of Electricity Cost Risks and Opportunities in the Gold Mining Industry (Ph.D. thesis), Department of Mechanical Engineering, North-West University Potchefstroom.

Vermeulen, J., Cilliers, C., Marais, J.H., 2017. Cost-effective compressor control to reduce oversupply of compressed air. In: Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE, pp. 1–7.

Wang, N., Wen, Z., Liu, M., Guo, J., 2016. Constructing an energy efficiency benchmarking system for coal production. Appl. Energy 169, 301–308.